CCSDS APPLICATIONS

PRESENTED AT THE

INTERNATIONAL TELEMETERING CONFERENCE

Session XVIII

October 30, 1997
Las Vegas, NV

FOREWORD

DAVID L. TOWNLEY
CCSDS General Secretary

The Consultative Committee for Space Data Systems (CCSDS) is an international organization of space agencies interested in mutually developing standard data handling techniques to support space research, including space science and applications, conducted exclusively for peaceful purposes. The Consultative Committee for Space Data Systems (CCSDS) was organized in January 1982. Since its inception the CCSDS has grown to a compliment of 10 Member space agencies and 23 Observer Agencies from around the globe. As of the date of this publication the CCSDS has published 25 Recommendations of which 17 have been adopted by the International Standards Organization (ISO).

The primary products of the CCSDS are technical Recommendations that guide internal developments of compatible standards within each participating space Agency. It is believed that the CCSDS activities will significantly enhance the planning and execution of future cooperative space missions. An intrinsic contribution of the CCSDS Recommendations is the expected higher degree of interoperability among Agencies that observe the Recommendations. The fundamental operating principle of the CCSDS is consensus. CCSDS Recommendations represent an approach that the Member Agencies agree is the best resolution feasible.

In addition to the overview of the CCSDS, the presentations contained herein describe some past and on-going experiences with implementation of the CCSDS Recommendations. We hope the contents of these presentations will stimulate a constructive dialogue among your peers as well as with members of the CCSDS supporting organizations and other standards development organizations.

Our intent here is to create the broadest possible awareness of the standards development activities within the space communications community and encourage participation in that development process by all who may be impacted. We hope you find this session informative and we welcome the opportunity to discuss in further detail the scope of our program and how it might relate to your activities.

The CCSDS Recommendations and their related ISO standards are available on the Internet at URL:

http://www.gsfc.nasa.gov/ccsds/ccsds_home.html

If you have any comments or questions on the CCSDS, please feel free to contact us at the telephone number or e-mail address provided below.

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Overview of the Consultative Committee for Space Data Systems (CCSDS)

International Telemetering Conference

Las Vegas, USA
30 October 1997

Adrian J. Hooke
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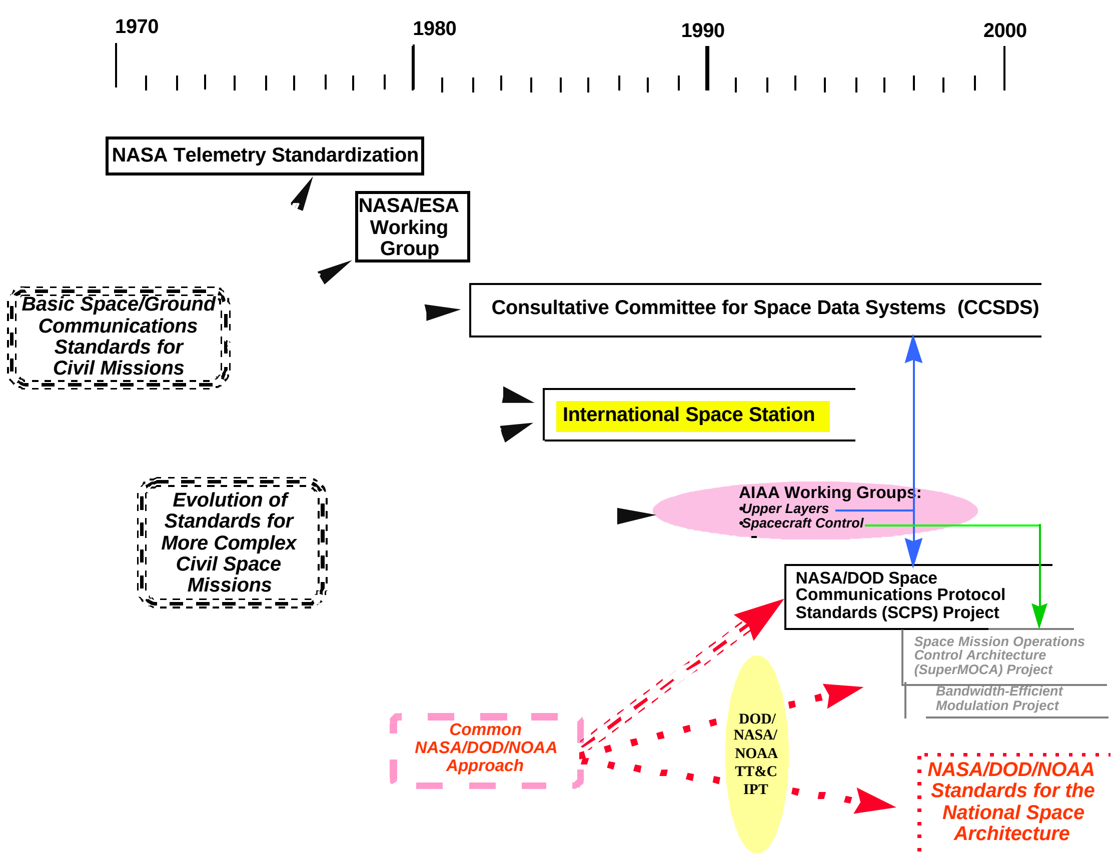
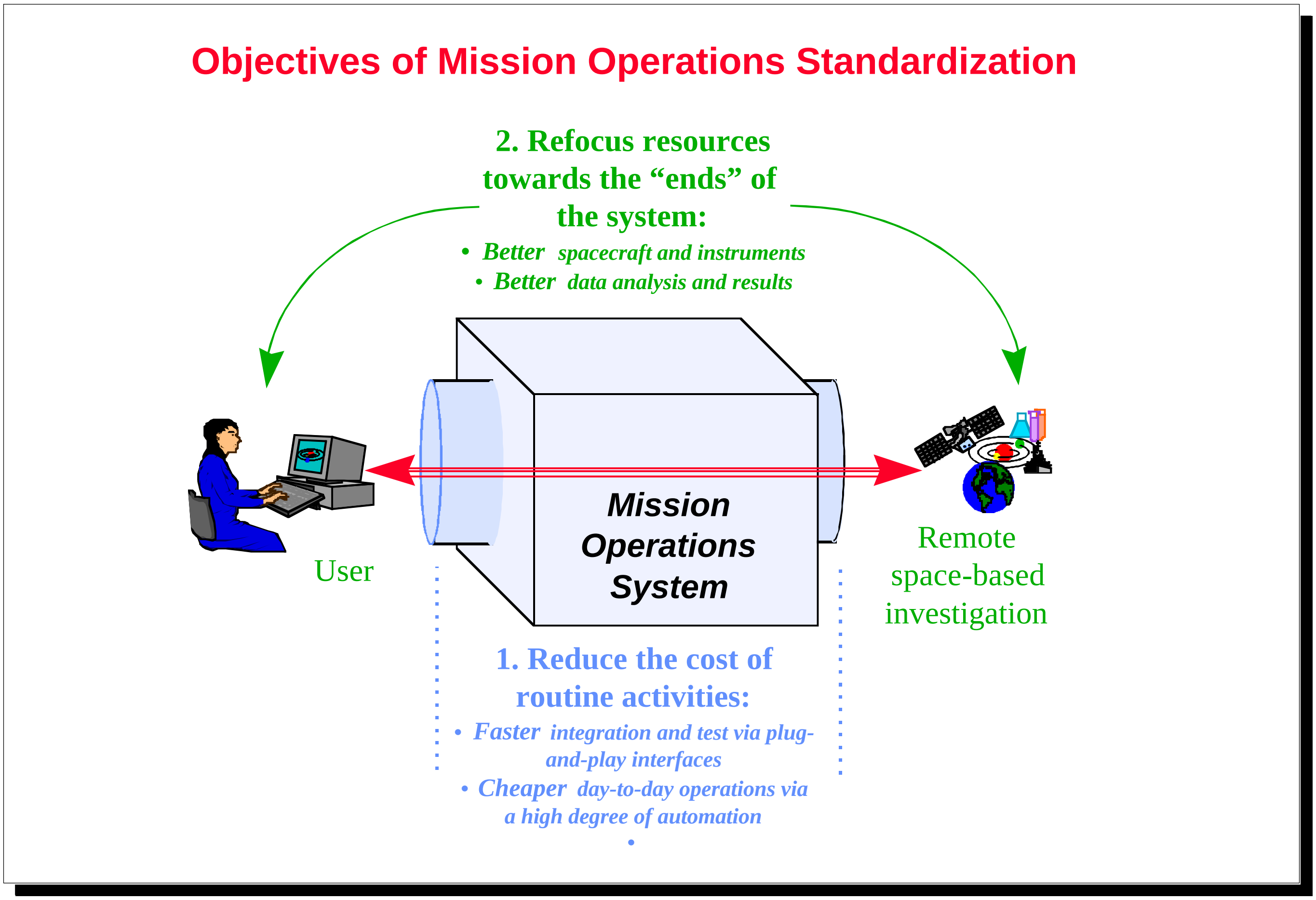
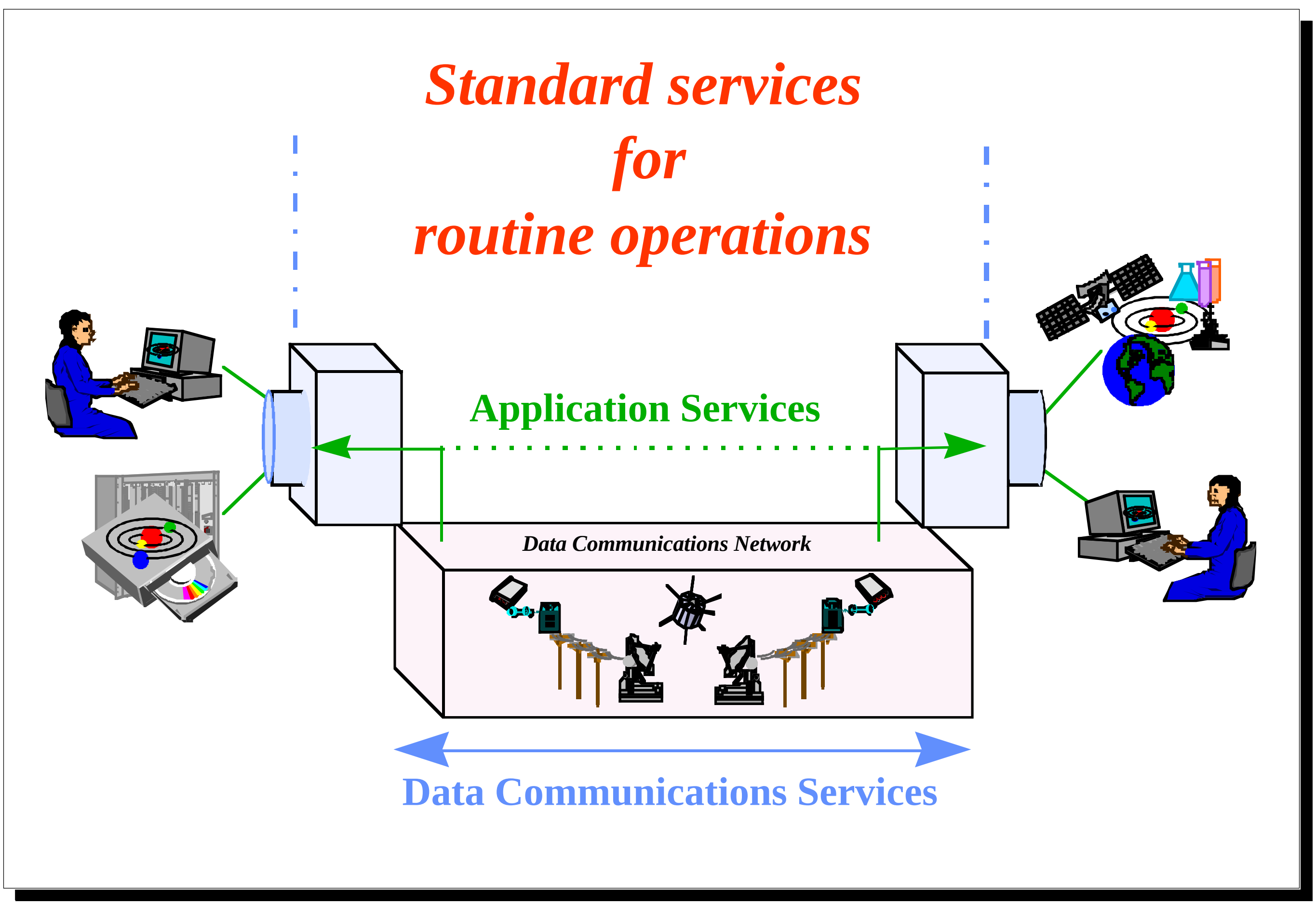
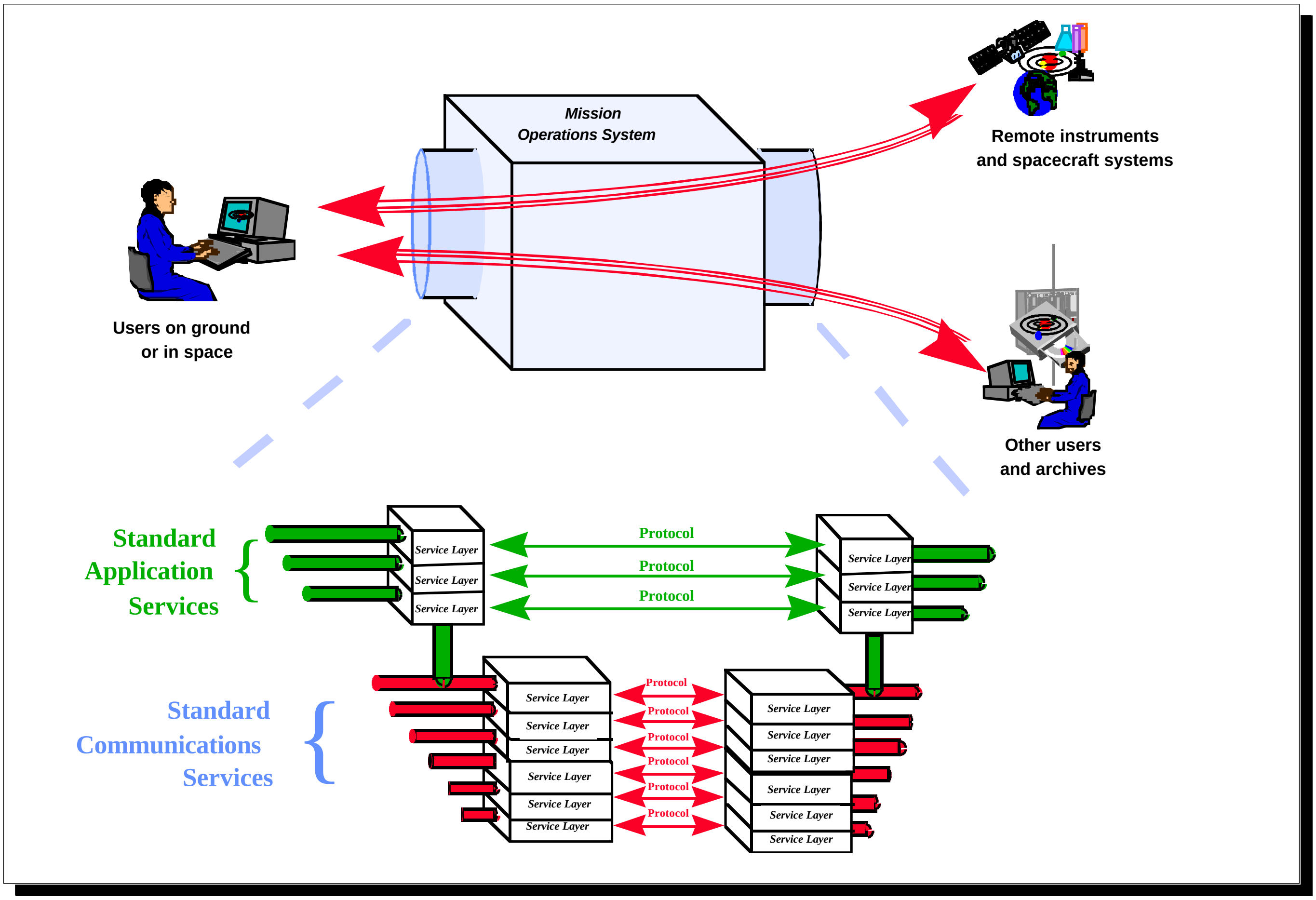
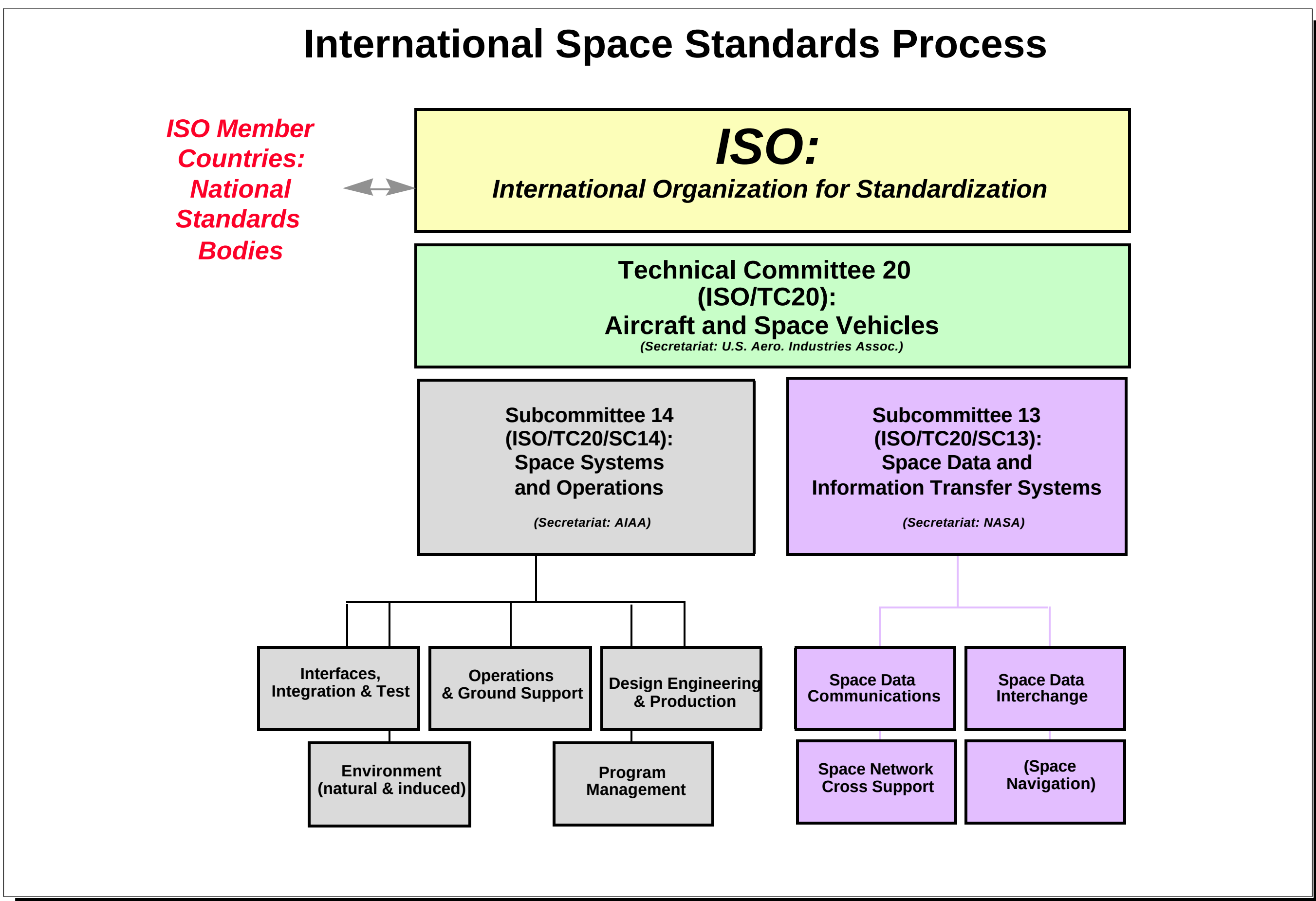
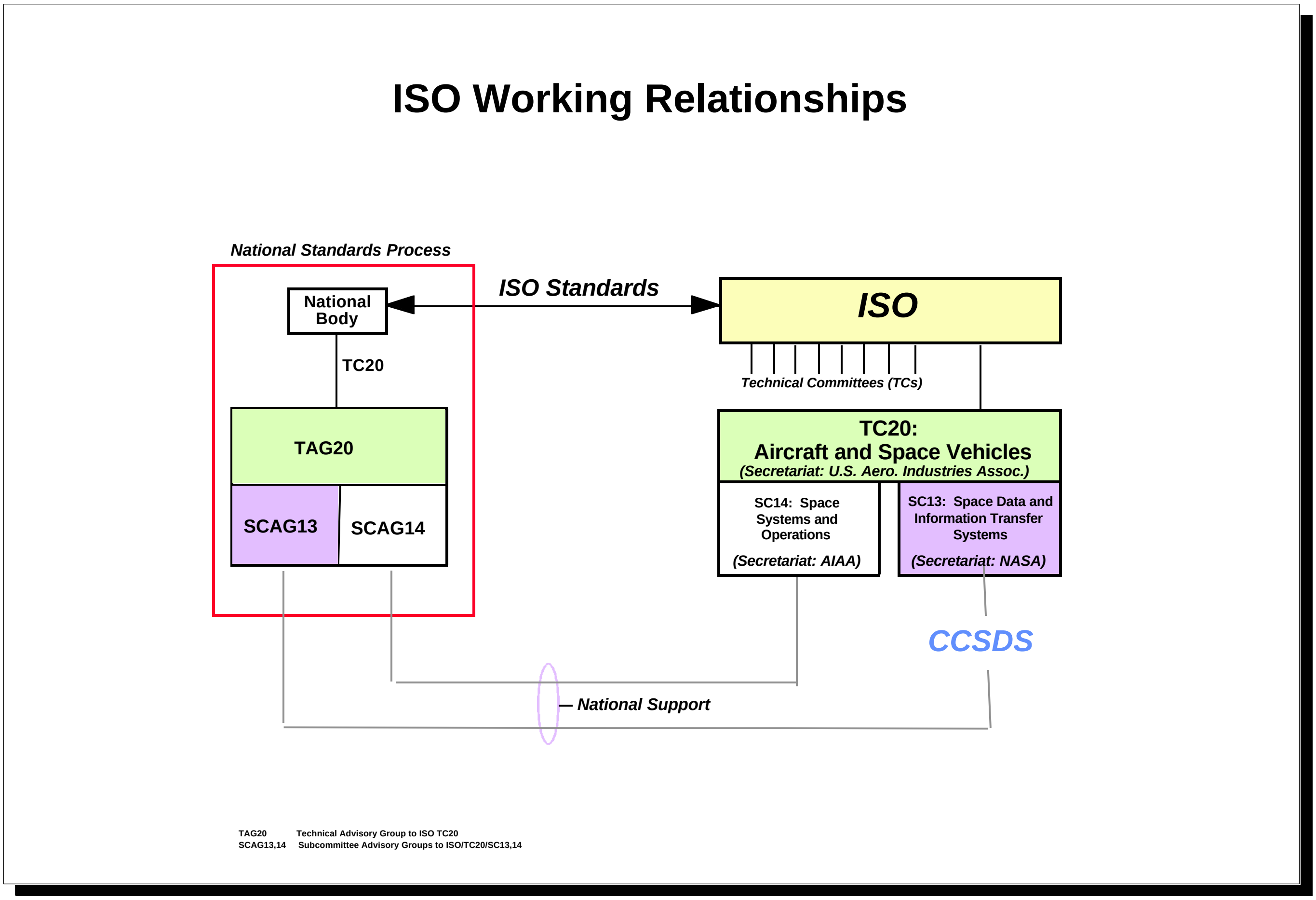


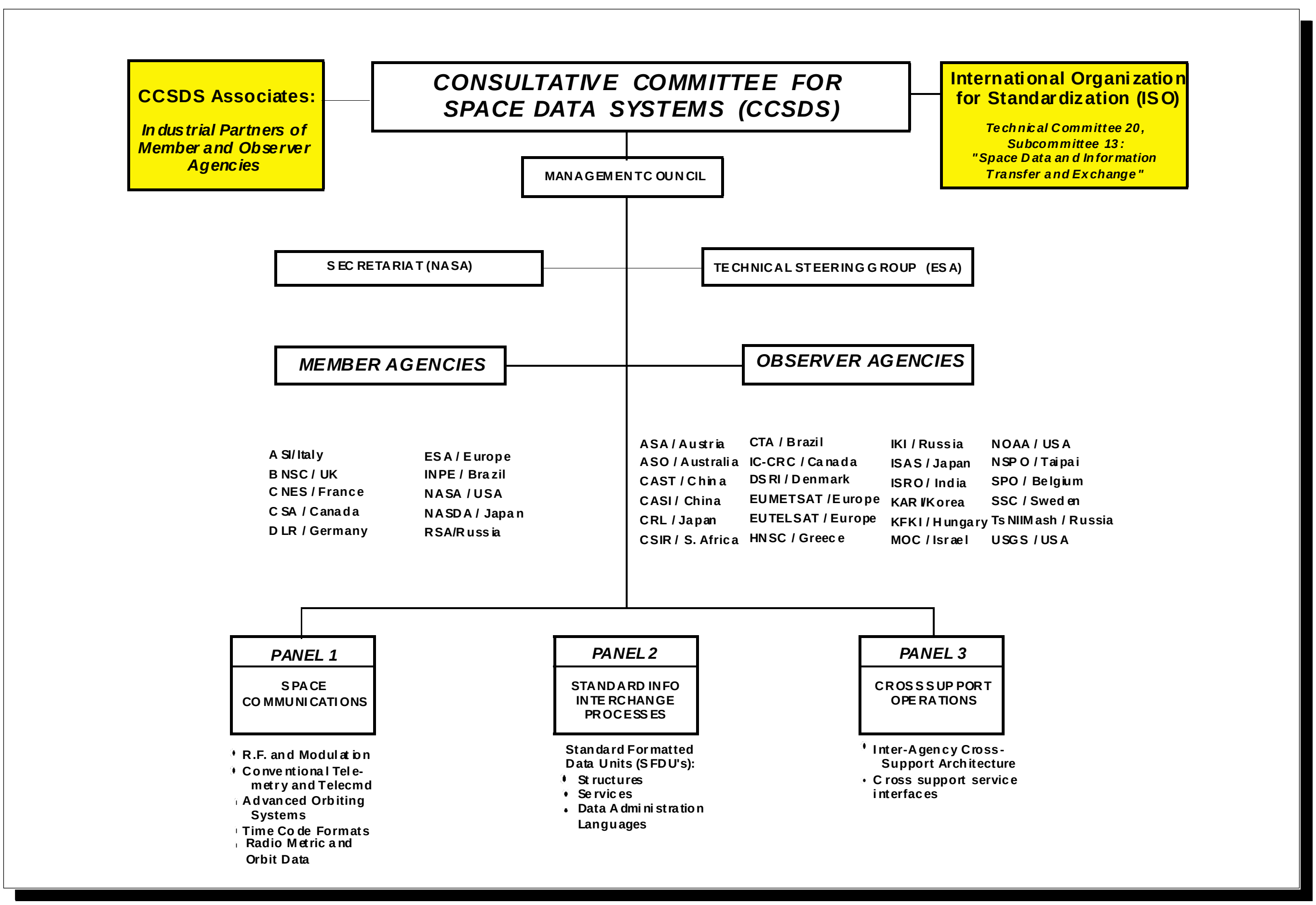

Objectives of Mission Operations Standardization
2. Refocus resources towards the “ends” of the system:
• Better spacecraft and instruments
• Better data analysis and results
User
Mission Operations System
Remote space-based investigation
1. Reduce the cost of routine activities:
• Faster integration and test via plug-and-play interfaces
• Cheaper day-to-day operations via a high degree of automation
•


Standard services for routine operations
Application Services
Data Communications Network
Data Communications Services

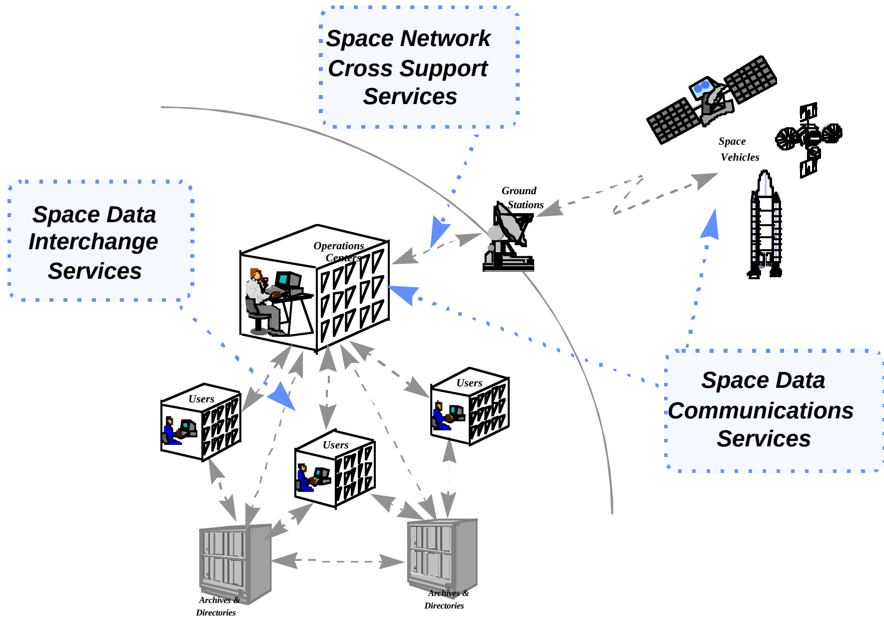

Mission
Operations System
Remote instruments
and spacecraft systems
Users on ground
or in space
Other users
and archives
Standard
Application
Services
Service Layer
Service Layer
Service Layer
Protocol
Protocol
Protocol
Service Layer
Service Layer
Service Layer
Standard
Communications
Services
Service Layer
Protocol
Service Layer

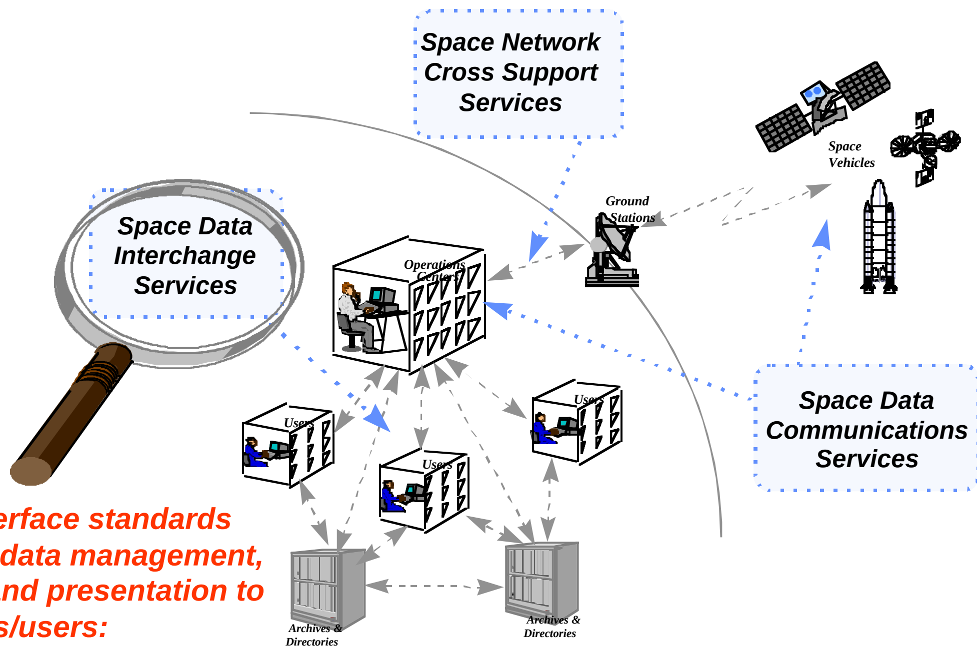

International Space Standards Process
ISO Member
Countries:
National
Standards
Bodies
ISO:
International Organization for Standardization
Technical Committee 20
(ISO/TC20):
Aircraft and Space Vehicles
(Secretariat: U.S. Aero. Industries Assoc.)
Subcommittee 14
(ISO/TC20/SC14):
Space Systems
and Operations
(Secretariat: AIAA)
Subcommittee 13
(ISO/TC20/SC13):
Space Data and
Information Transfer Systems
(Secretariat: NASA)
Interfaces,
Integration & Test
Operations
& Ground Support
Design Engineering
& Production
Environment
(natural & induced)
Program
Management
Space Data
Communications
Space Data
Interchange
Space Network
Cross Support
(Space
Navigation)


ISO Working Relationships
National Standards Process
National Body
TC20
TAG20
SCAG13
SCAG14
ISO Standards
ISO
Technical Committees (TCs)
TC20:
Aircraft and Space Vehicles
(Secretariat: U.S. Aero. Industries Assoc.)
SC14: Space Systems and Operations
(Secretariat: AIAA)
SC13: Space Data and Information Transfer Systems
(Secretariat: NASA)
CCSDS
National Support
TAG20 Technical Advisory Group to ISO TC20
SCAG13,14 Subcommittee Advisory Groups to ISO/TC20/SC13,14


CCSDS Associates:
Industrial Partners of Member and Observer Agencies
CONSULTATIVE COMMITTEE FOR SPACE DATA SYSTEMS (CCSDS)
International Organization for Standardization (ISO)
Technical Committee 20, Subcommittee 13: "Space Data and Information Transfer and Exchange"
MANAGEMENT COUNCIL
SECRETARIAT (NASA)
TECHNICAL STEERING GROUP (ESA)
MEMBER AGENCIES
OBSERVER AGENCIES
ASI/Italy
BNSC / UK
CNES / France
CSA / Canada
DLR / Germany
ESA / Europe
INPE / Brazil
NASA / USA
NASDA / Japan
RSA/Russia
ASA / Austria
ASO / Australia
CAST / China
CASI / China
CRL / Japan
CSIR / S. Africa
CTA / Brazil
IC-CRC / Canada
DSRI / Denmark
EUMETSAT / Europe
EUTELSAT / Europe
HNSC / Greece
IKI / Russia
ISAS / Japan
ISRO / India
KARI/Korea
KFKI / Hungary
MOC / Israel
NOAA / USA
NSPO / Taipai
SPO / Belgium
SSC / Sweden
TsNIIMash / Russia
USGS / USA
PANEL 1
SPACE COMMUNICATIONS
R.F. and Modulation
Conventional Telemetry and Telecmd
Advanced Orbiting Systems
Time Code Formats
Radio Metric and Orbit Data
PANEL 2
STANDARD INFO INTERCHANGE PROCESSES
Standard Formatted Data Units (SFDU's):
Structures
Services
Data Administration Languages
PANEL 3
CROSS SUPPORT OPERATIONS
Inter-Agency Cross-Support Architecture
Cross support service interfaces

Principal Domains of Space Mission Operations Standardization

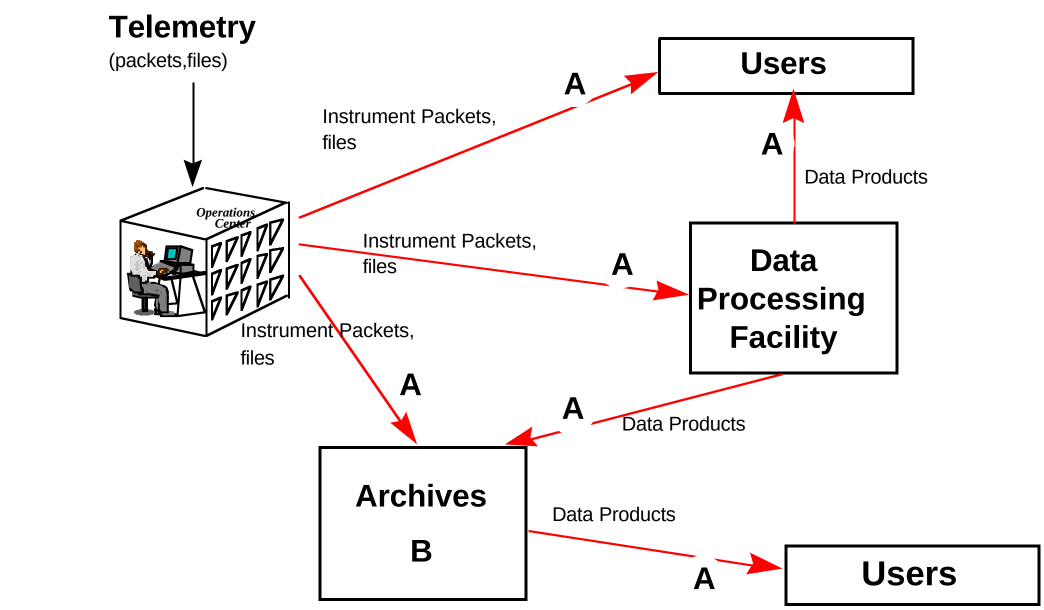




Generic interface standards supporting data management, archiving and presentation to applications/users:

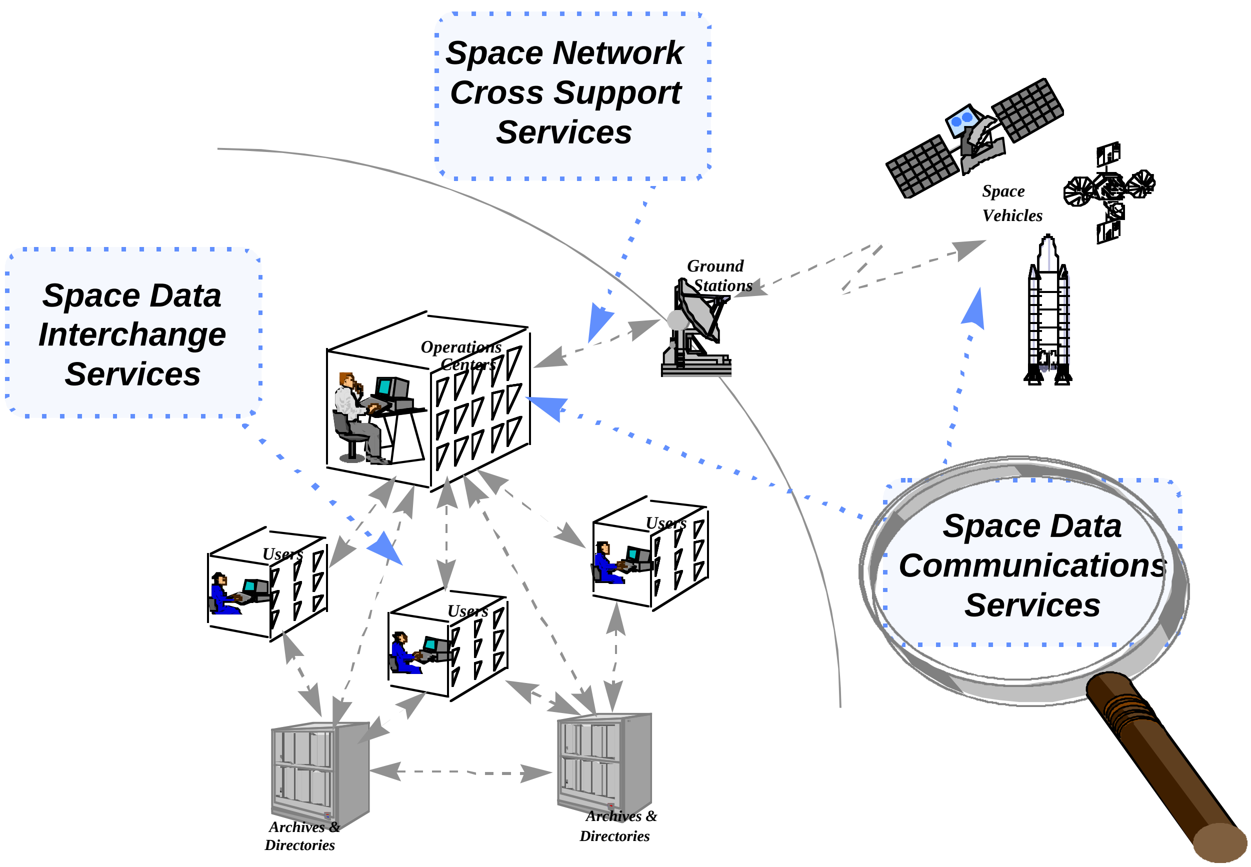
- **Data description**
  formal description languages supporting automated parsing of associated data objects
- **Data packaging**
  Encapsulation and identification of any data objects with any formats
- **Unambiguous data identification**
  International registration of data descriptions

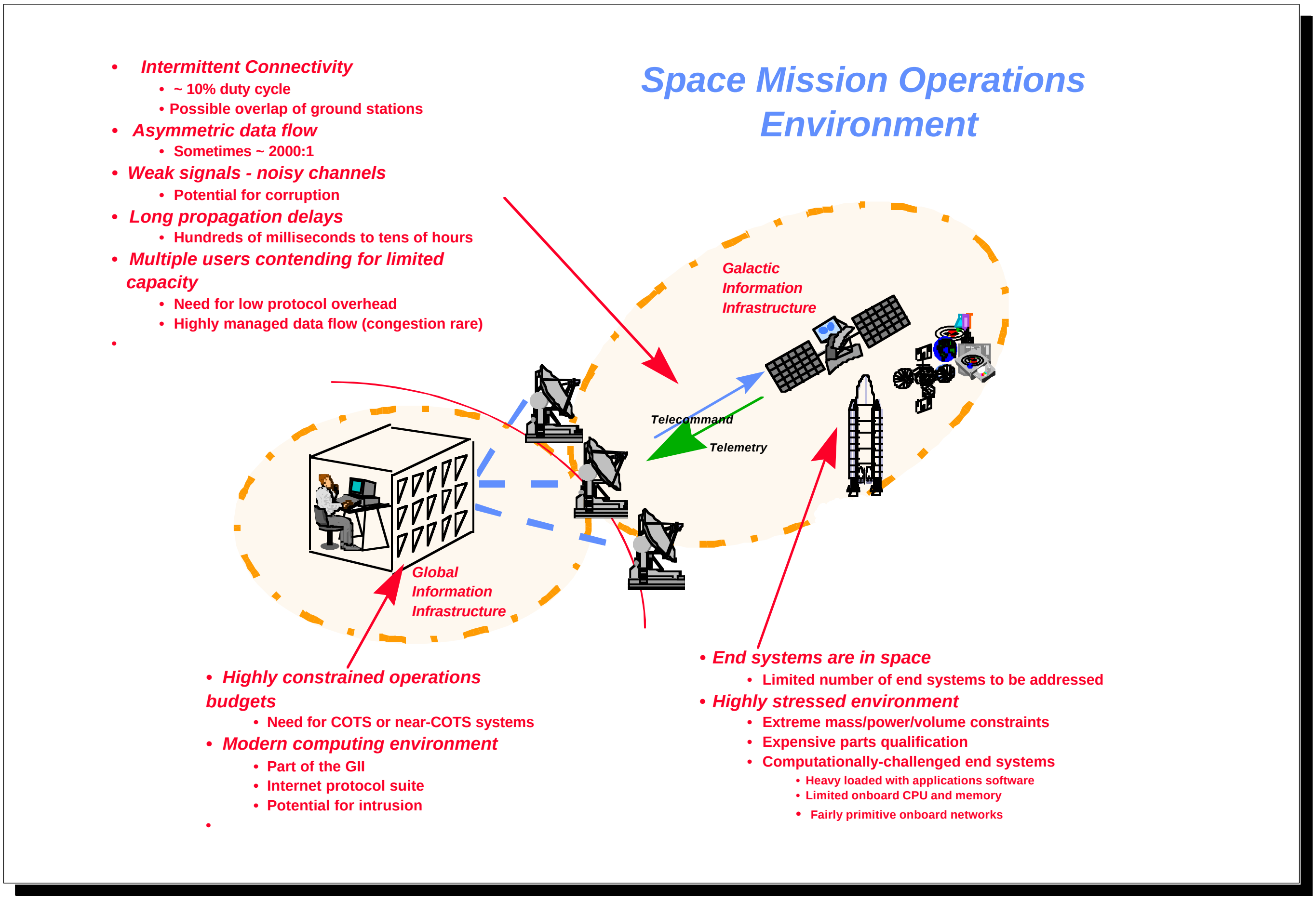
Space Data Interchange Standards

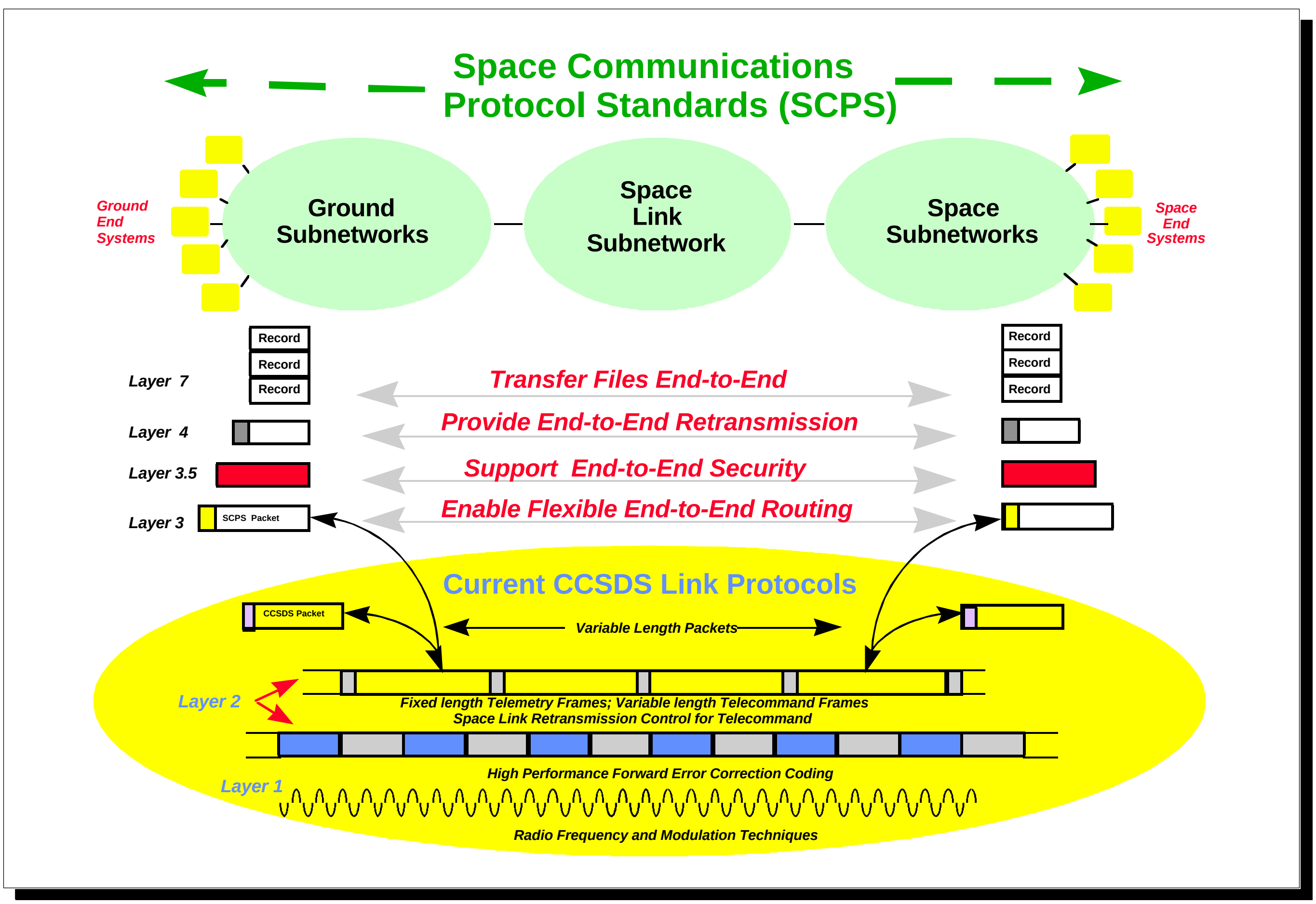


A Generalized Interface Standards

B Archive Internal Standards



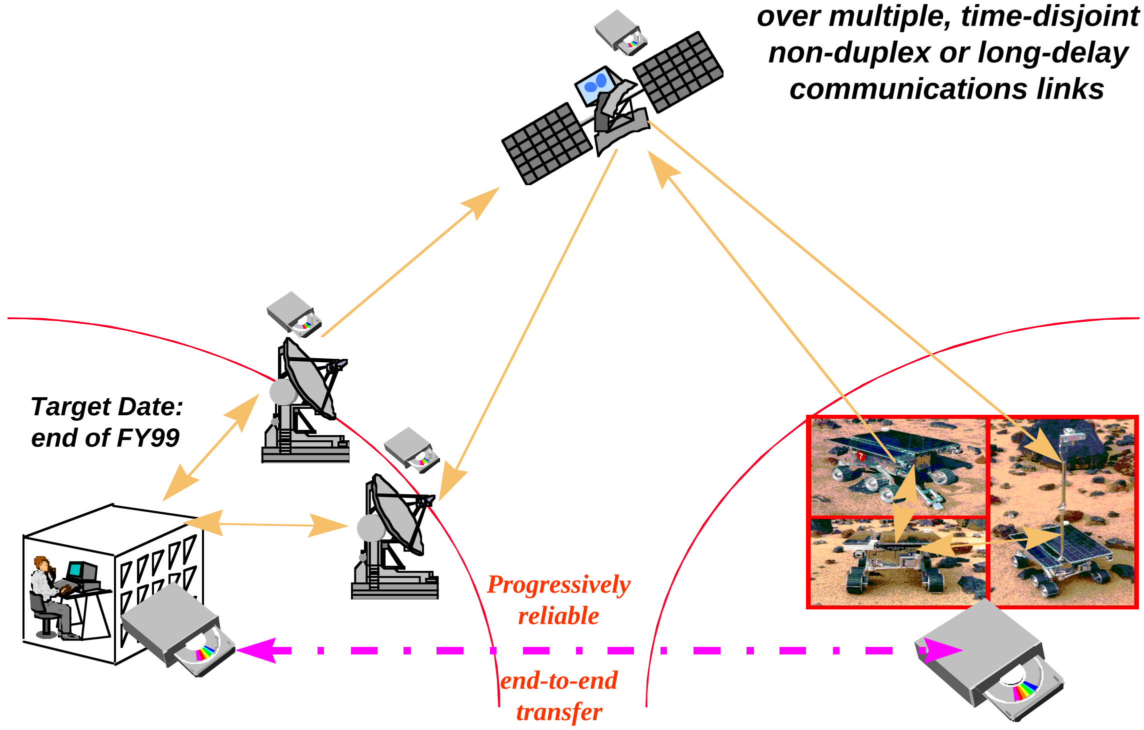

Space Mission Operations Environment
• Intermittent Connectivity
• ~ 10% duty cycle
• Possible overlap of ground stations
• Asymmetric data flow
• Sometimes ~ 2000:1
• Weak signals - noisy channels
• Potential for corruption
• Long propagation delays
• Hundreds of milliseconds to tens of hours
• Multiple users contending for limited capacity
• Need for low protocol overhead
• Highly managed data flow (congestion rare)
Galactic Information Infrastructure
Telecommand
Telemetry
Global Information Infrastructure
• Highly constrained operations budgets
• Need for COTS or near-COTS systems
• Modern computing environment
• Part of the GII
• Internet protocol suite
• Potential for intrusion
• End systems are in space
• Limited number of end systems to be addressed
• Highly stressed environment
• Extreme mass/power/volume constraints
• Expensive parts qualification
• Computationally-challenged end systems
• Heavy loaded with applications software
• Limited onboard CPU and memory
• Fairly primitive onboard networks

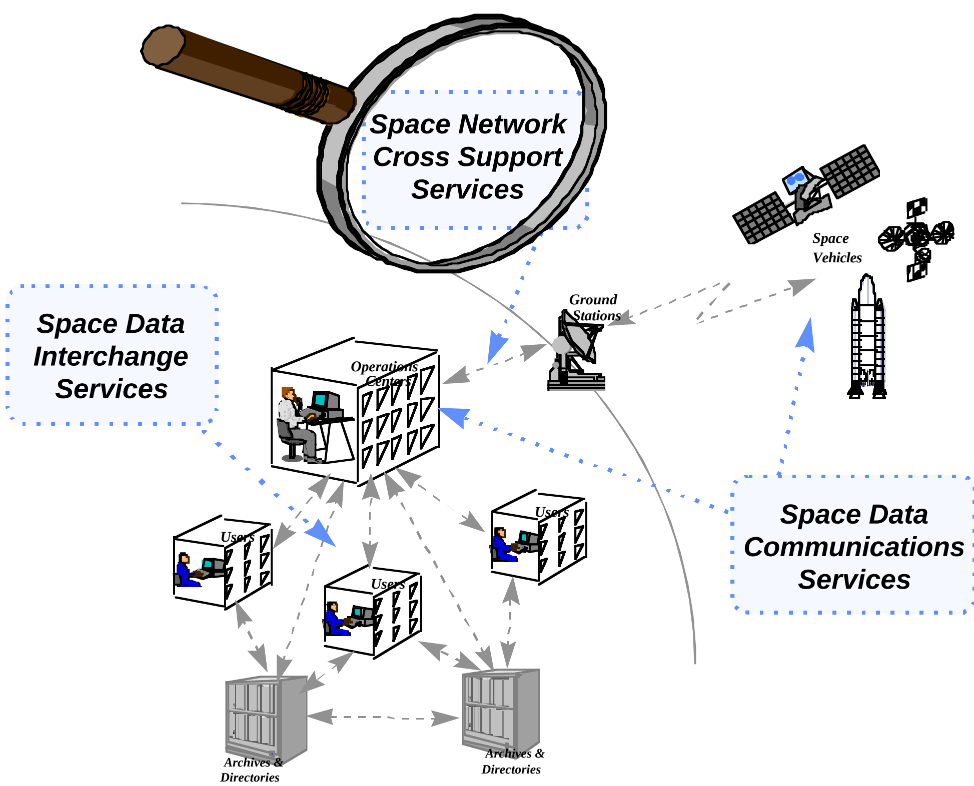

Space Communications Protocol Standards (SCPS)
Ground End Systems
Ground Subnetworks
Space Link Subnetwork
Space Subnetworks
Space End Systems
Record
Record
Record
Layer 7
Transfer Files End-to-End
Layer 4
Provide End-to-End Retransmission
Layer 3.5
Support End-to-End Security
Layer 3
SCPS Packet
Enable Flexible End-to-End Routing
Current CCSDS Link Protocols
CCSDS Packet
Variable Length Packets
Layer 2
Fixed length Telemetry Frames; Variable length Telecommand Frames
Space Link Retransmission Control for Telecommand
High Performance Forward Error Correction Coding
Layer 1
Radio Frequency and Modulation Techniques

SCPS Phase-3: Protocol Variants

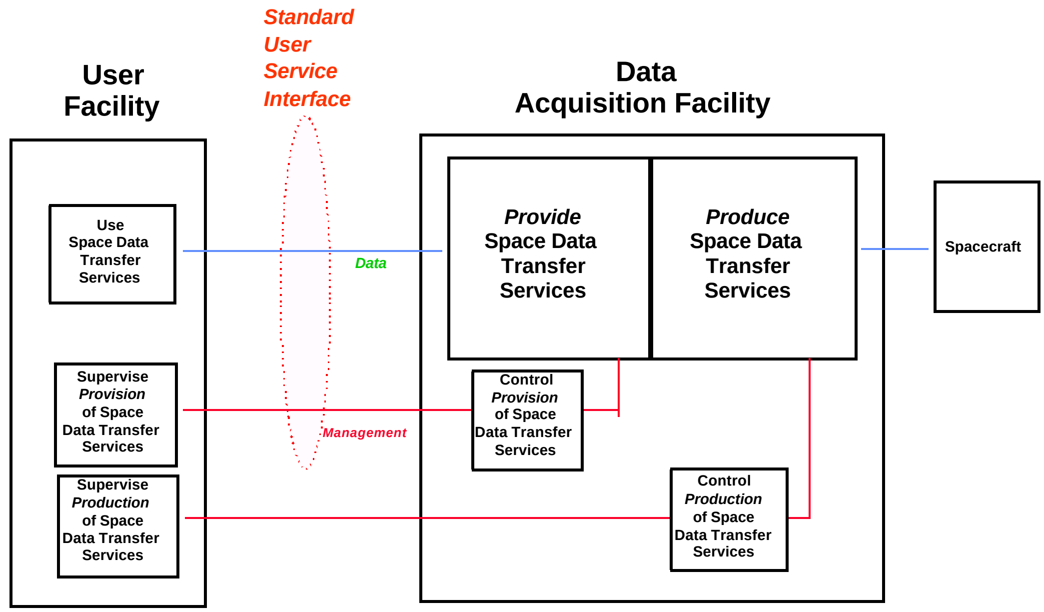
"Protocol-X":

store and forward end-to-end File transfer over multiple, time-disjoint non-duplex or long-delay communications links



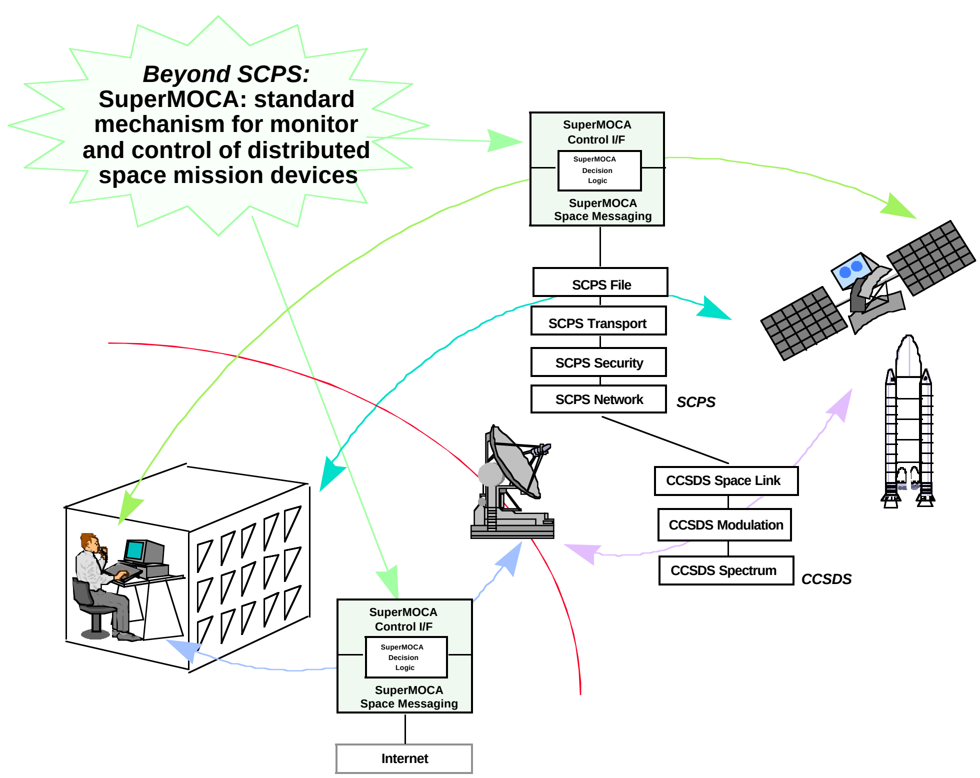


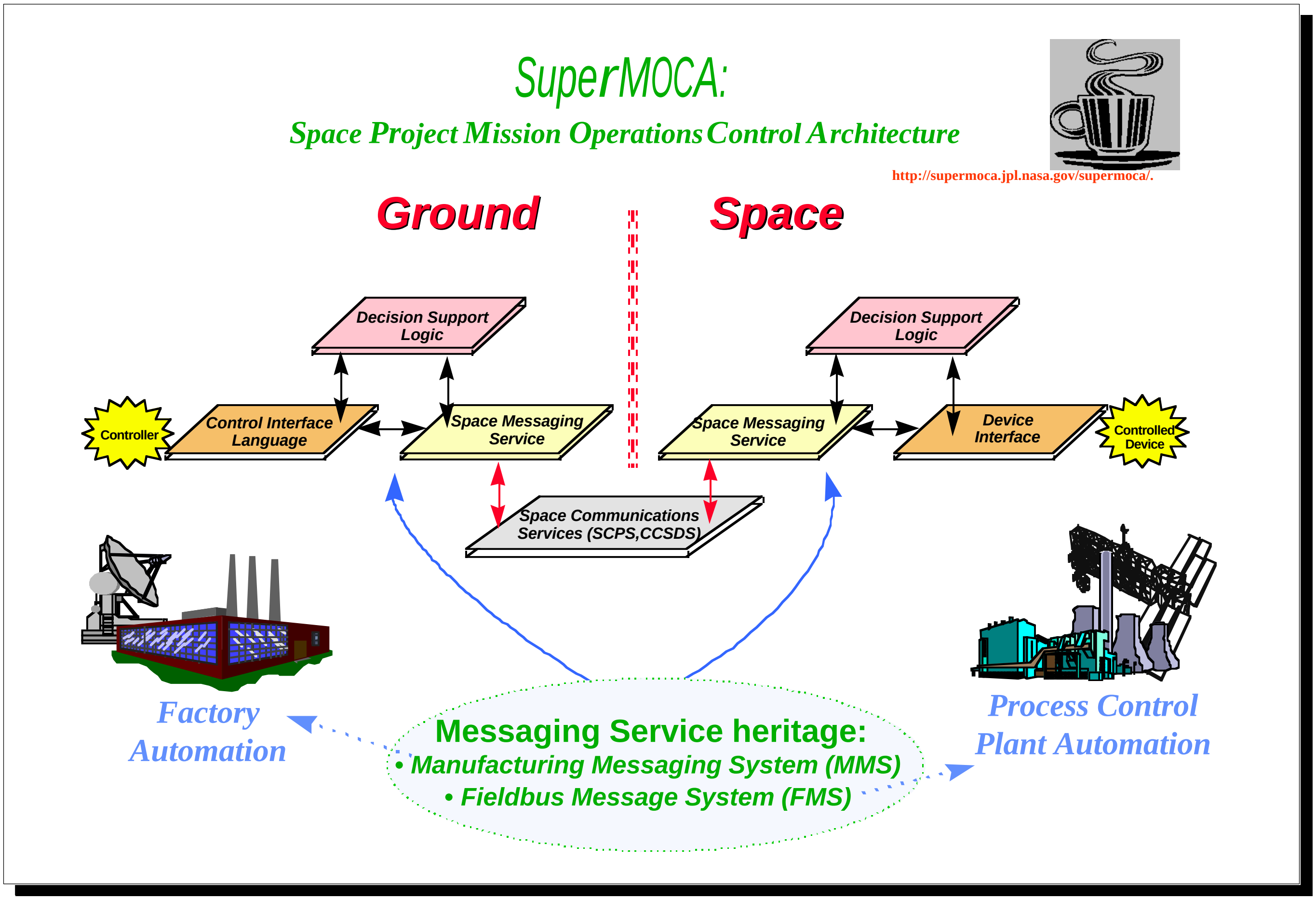
Space Link Extension Services



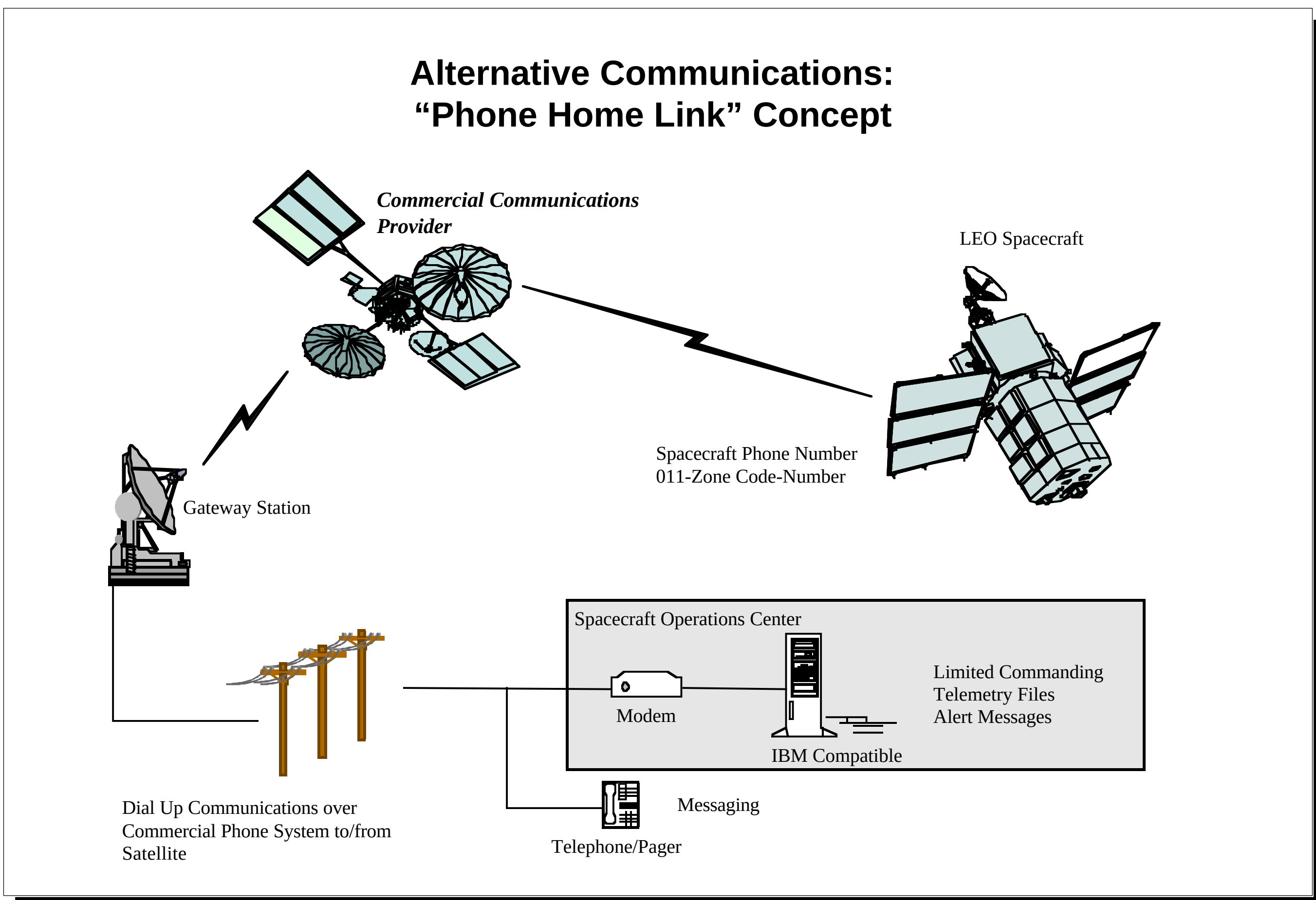
Provision: extending a user-selectable data transfer service interface to a user

Production: creating the underlying user-independent space/ground data communications capability



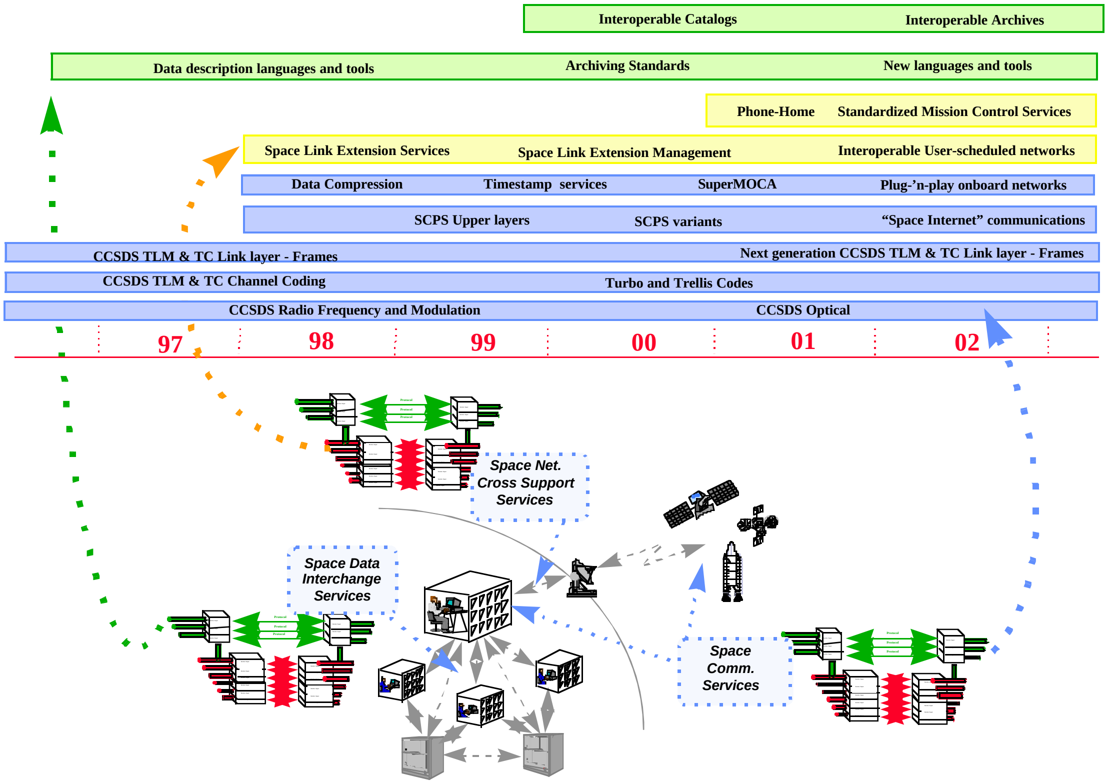


SuperMOCA:
Space Project Mission Operations Control Architecture
http://supermoca.jpl.nasa.gov/supermoca/.
Ground
Space
Decision Support Logic
Decision Support Logic
Controller
Control Interface Language
Space Messaging Service
Space Messaging Service
Device Interface
Controlled Device
Space Communications Services (SCPS,CCSDS)
Factory Automation
Process Control Plant Automation
Messaging Service heritage:
• Manufacturing Messaging System (MMS)
• Fieldbus Message System (FMS)

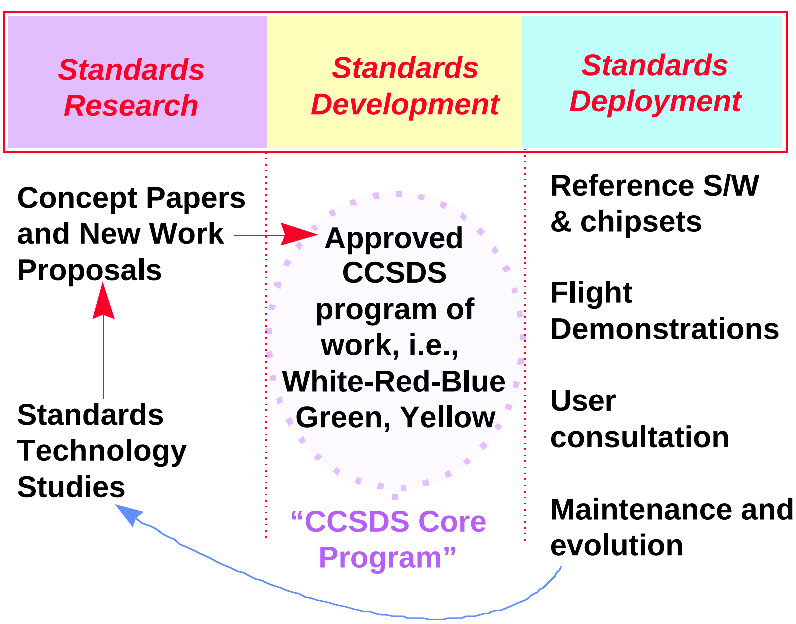


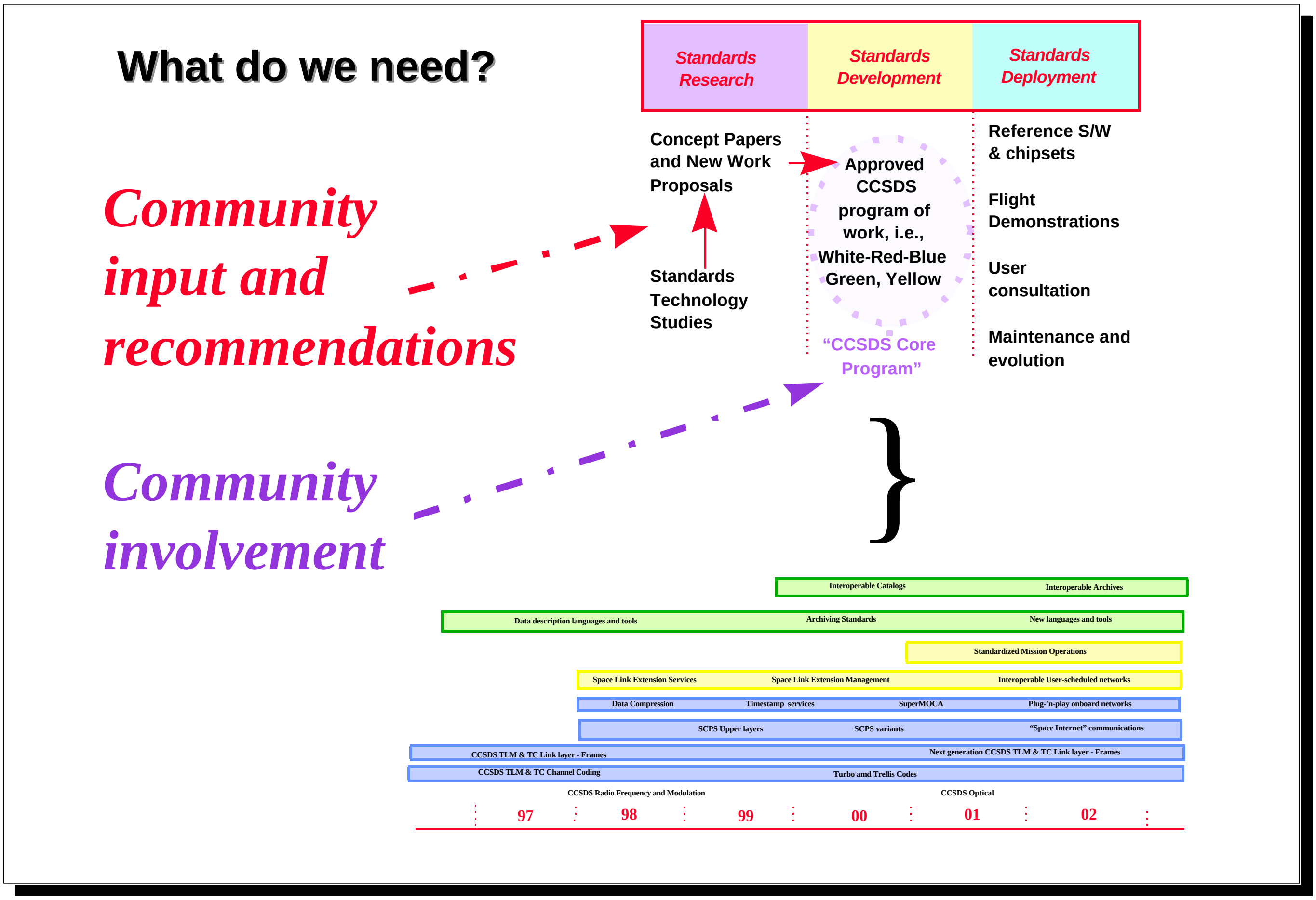
Alternative Communications:
“Phone Home Link” Concept
Commercial Communications Provider
LEO Spacecraft
Spacecraft Phone Number
011-Zone Code-Number
Gateway Station
Spacecraft Operations Center
Modem
IBM Compatible
Limited Commanding
Telemetry Files
Alert Messages
Messaging
Telephone/Pager
Dial Up Communications over
Commercial Phone System to/from
Satellite

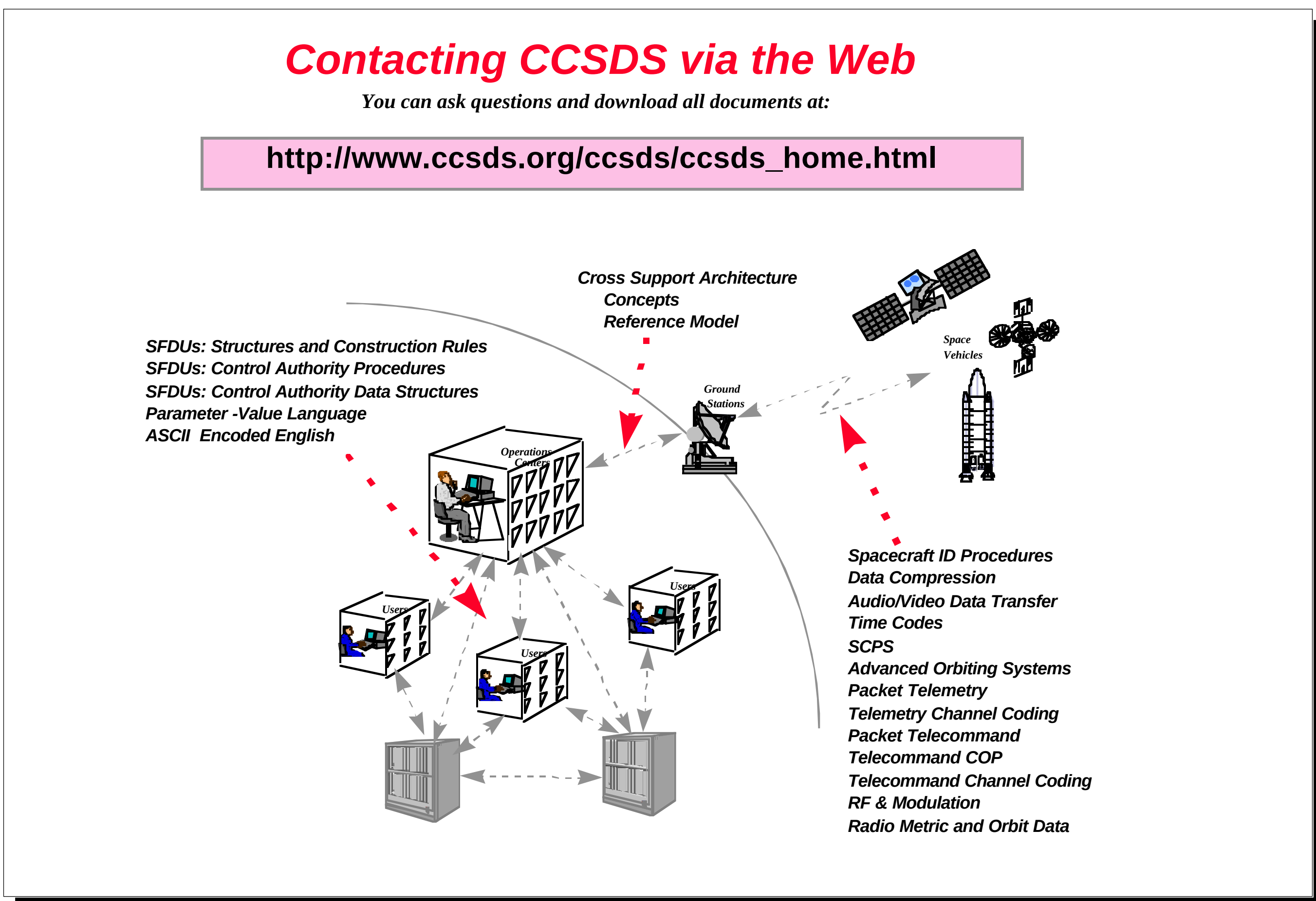
Emerging Standards Roadmap



Standards Lifecycle




What do we need?
Standards Research
Standards Development
Standards Deployment
Concept Papers and New Work Proposals
Standards Technology Studies
Approved CCSDS program of work, i.e., White-Red-Blue Green, Yellow
"CCSDS Core Program"
Reference S/W & chipsets
Flight Demonstrations
User consultation
Maintenance and evolution
Community input and recommendations
Community involvement
Interoperable Catalogs
Interoperable Archives
Data description languages and tools
Archiving Standards
New languages and tools
Standardized Mission Operations
Space Link Extension Services
Space Link Extension Management
Interoperable User-scheduled networks
Data Compression
Timestamp services
SuperMOCA
Plug-'n-play onboard networks
SCPS Upper layers
SCPS variants
"Space Internet" communications
CCSDS TLM & TC Link layer - Frames
Next generation CCSDS TLM & TC Link layer - Frames
CCSDS TLM & TC Channel Coding
Turbo amd Trellis Codes
CCSDS Radio Frequency and Modulation
CCSDS Optical
97
98
99
00
01
02


Contacting CCSDS via the Web
You can ask questions and download all documents at:
http://www.ccsds.org/ccsds/ccsds_home.html
Cross Support Architecture
Concepts
Reference Model
SFDUs: Structures and Construction Rules
SFDUs: Control Authority Procedures
SFDUs: Control Authority Data Structures
Parameter -Value Language
ASCII Encoded English
Ground Stations
Space Vehicles
Operations Center
User
User
User
Spacecraft ID Procedures
Data Compression
Audio/Video Data Transfer
Time Codes
SCPS
Advanced Orbiting Systems
Packet Telemetry
Telemetry Channel Coding
Packet Telecommand
Telecommand COP
Telecommand Channel Coding
RF & Modulation
Radio Metric and Orbit Data

EDOS EXPERIENCES WITH CCSDS IN SUPPORT OF THE EOS SPACECRAFT

Alan T. Johns
Alexander Krimchansky

ABSTRACT

The Earth Observing System (EOS) Data and Operations System (EDOS) is currently being developed to support CCSDS command and telemetry interfaces with NASA's fleet of EOS spacecraft. As launch of the EOS AM-1 spacecraft draws near and detailed design of the EOS PM-1 spacecraft begins, the EDOS Project has collected a series of lessons learned with regard to CCSDS interfaces with these spacecraft. This paper discusses the successes achieved and the pitfalls encountered in implementing space-to-ground CCSDS protocols and makes recommendations for changes and enhancements to the protocols to maximize future mission successes.

KEY WORDS

NASA, EDOS, CCSDS Services, Path Service, AM-1 Spacecraft, PM-1 Spacecraft

INTRODUCTION

The EOS spacecraft are the cornerstone of NASA's Mission to Planet Earth, a massive, worldwide effort to observe, monitor and assess large-scale environmental processes, focusing on climate change. Common features among all EOS spacecraft are compliance with CCSDS Recommendations and high data rates (up to 150 Megabits per second [Mbps]). The EDOS is being built at NASA's Goddard Space Flight Center to process all EOS satellite data to level zero format. As the EDOS Project works with a number of satellite manufacturers and science instrument teams, some interesting interpretations of the CCSDS Recommendations have been encountered.

REED-SOLOMON ERROR CONTROL

At the Channel Access Data Unit (CADU) level, Reed-Solomon error control has proven to be of great benefit. Reed-Solomon is much preferred over the cyclic redundancy code (CRC) implementation previously recommended by the CCSDS Recommendation for Space Data System Standards, *Packet Telemetry* (reference [1]; hereafter referred to as the Packet Telemetry Blue Book). The CRC schema tended to flag a large portion of frames as having errors but gave no indication of the severity of the errors. This caused packet reassembly logic to be excessively complex in order to compensate for all possible errors the CRC schema was capable of detecting in a packet header.

The high data rates associated with the AM-1 downlink (150 Mbps) forced EDOS to implement a hardware solution to perform Reed-Solomon corrections in real time. At rates of 5 Mbps or less, software solutions have been shown to be adequate. Recent advancements in microprocessor speeds may enable a software solution for processing data at higher rates; software processing rates have increased from 0.5 Mbps to 9 Mbps in under 5 years. A software solution for high-rate Reed-Solomon processing is preferable to a hardware solution in that a software solution would reduce system lifecycle costs and maximize system portability.

CADU SECONDARY HEADERS

The Packet Telemetry Blue Book allows secondary headers on frames to be defined in such a way as to enable selective processing of CADUs. The CCSDS Recommendation for Space Data System Standards, *Advanced Orbiting Systems, Networks and Data Links: Architectural Specification* (reference [2]; hereafter referred to as the AOS Blue Book) encourages the use of distinct virtual channel identifiers (VCIDs), but this prevents selective subsampling of virtual channels.

The EDOS experience has shown that a frame level secondary header can be very beneficial. For AM-1, the instrument teams have requested that EDOS be able to process and forward selectable packets collected during a downlink session with the spacecraft. With the Packet Telemetry Blue Book recommendations, it was possible to predefine a flag within the frame secondary header that would have allowed a telemetry processing system to route the marked packets to the end users without performing packet reassembly services on the entire data stream received from the spacecraft. Instead, following the constraints of the AOS Blue Book, EDOS has to process the entire data stream in order to find the desired packets—100 percent of the data must be processed to find the desired subsample of packets (typically around 2 percent of the data stream). Another use of a CADU secondary header could be for time stamps. This would allow CADUs to be sorted by time and also could make spacecraft time correlation easier.

PACKET SEGMENTATION

The Packet Telemetry Blue Book allows packet segmentation in order to handle large (tens of kilobits) packets by segmenting the packets on the spacecraft. The ground system was then responsible for packet reassembly. The AOS Blue Book recognizes only Version-1 packets and includes specific verbiage that packet segmentation is not part of the Path protocol. However, Bits 16 and 17 in the packet header are still present as “Sequence Flags”, and new users do not always recognize that the flags are not part of the Path Service and try to use flags as they were used with Version-2 packets.

An instrument on the PM-1 spacecraft wanted to use the flags to break up their large packets. This use of the flags was found too late in the spacecraft design lifecycle to change, so now special post-level zero processing is necessary. The instrument’s 1800-bit packets are broken up into a 1024-bit packet (Application Process Identifier (APID) x) and remainder (APID x+1). EDOS produces two datasets, one for APID x and another for APID x+1, and the user is responsible for merging the datasets back to their natural formats. EDOS is unable to perform this merger because the merge process requires knowledge of the instrument's Level 1 processing to adequately handle data gaps by combining or filling them. The EDOS Project recommends renaming the "Sequence Flag" field and updating the recommendations to provide a better definition and explanation of the field's function.

JUDICIOUS USE OF APIDS

An instrument on the AM-1 spacecraft has a hybrid packet that combines engineering and science data into a single packet with a unique APID (see Figure 1). The instrument team probably created the hybrid packet to fill an otherwise incomplete packet instead of using smaller packets or putting fill data in the packet. The use of the hybrid packet forces EDOS to utilize special processing to create a dataset with three unique APIDs, ordered by time. This special processing could have been avoided if the instrument team had realized that data was being processed by APID with the expectation that APIDs are assigned by logical function.

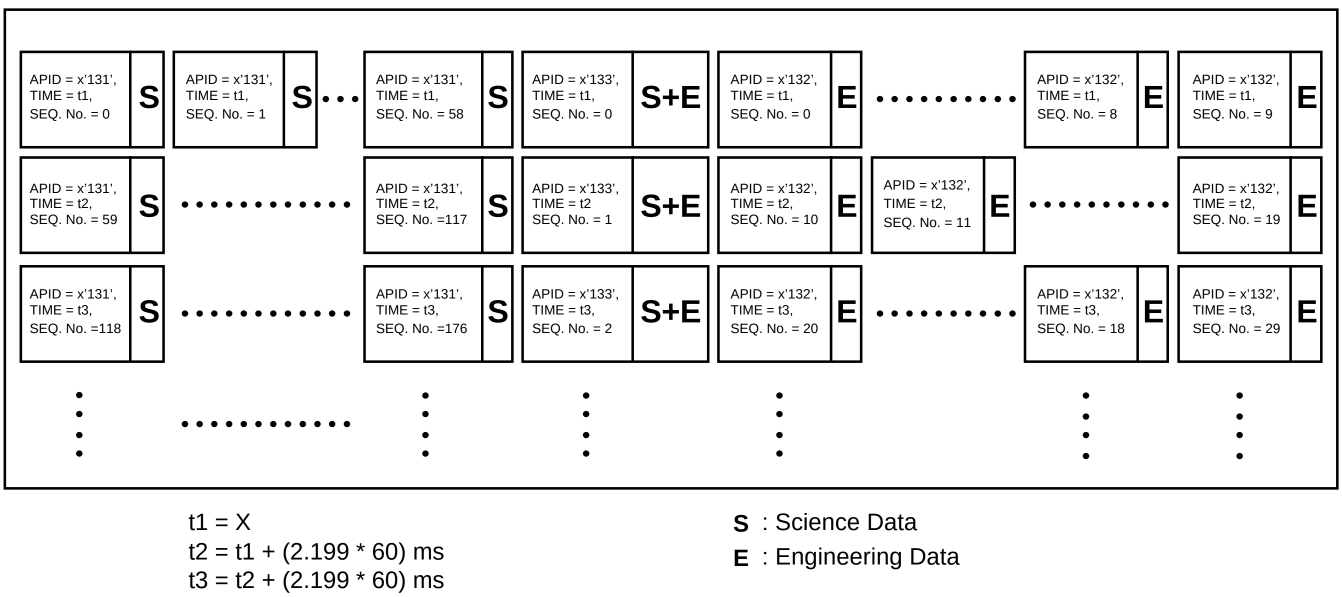


Figure 1. Hybrid Packets

Another instrument on AM-1 increments the sequence number on packets with the same APID until an "upset" takes place (see Figure 2). The upset causes the instrument software to change APID numbers of the affected packets, but the sequence number begins with the sequence number of the upset. Processing continues until the upset has been corrected, and then the software switches back to the routine APID, starting at the last sequence numbers of the upset APID. Each APID needs to have its own unique monotonically increasing sequence number and progression. Ideally, the instrument software should have started the sequence number at zero after the jump to the upset APID, and then after the switch back to the original APID, restarted the sequence number at the sequence number of the upset plus one.

EDOS will report missing packets (gap in sequence numbers for the routine APID) for this instrument's data. Again, an end user failed to recognize the independence of APIDs. The EDOS Project recommends that the Logical Data Path become synonymous with or identical to the APID. The assignment of APIDs should be given careful consideration—not too many (not one for every parameter), not too few, and in logical groupings.

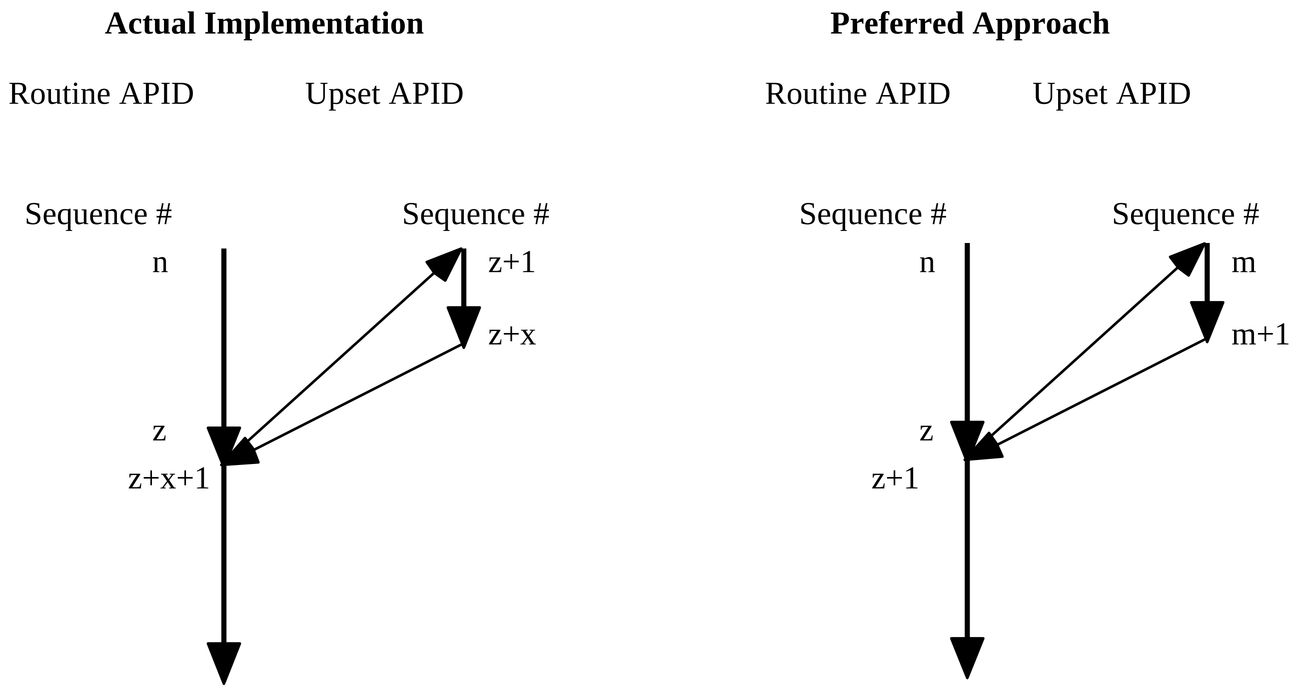


Figure 2. Sequence Number Jumps

TIME CODES

Time codes are addressed in Annex A, Addendum on CCSDS Packet Timetagging, of the AOS Blue Book. This addendum should be incorporated into the main document since, as an annex, it is not always read or followed. Every packet generated should have its own unique timetag. An instrument flying on both the AM-1 spacecraft and the PM-1 spacecraft generates up to 1200 packets with the same timetag, but each of these packets has a unique sequence number, making each packet uniquely identifiable in sequential transmissions. The combination of timetag and sequence number should be absolutely unique. Relying on sequence numbers for satellites with the high data rates of the EOS program causes problems when sequence numbers wrap around and, in the case of selective retransmissions, make preserving packet sequence nearly impossible. Updating the timetag on each packet guarantees that the original packet sequence can always be preserved under any circumstance.

STANDARD LEVEL ZERO PROCESSING FORMATS

Science users are acutely aware that different ground systems have different formats for level zero data products. This is to be somewhat expected, given that different space agencies tend to have unique ground system implementations. However, even within NASA, there are cases where science teams responsible for identical instruments flown on different spacecraft have to process multiple level zero product formats due to differences in ground system engineering. It should not be difficult to expand the CCSDS Recommendations to include a common format for level zero data. This would be particularly beneficial to the Earth science community, given that community's emphasis on data sharing.

CONCLUSION

The CCSDS Recommendations are an excellent means of ensuring commonality and standardization among all components of a space data system. Even though this paper makes a number of recommendations for enhancements to the CCSDS protocols, EDOS experiences with CCSDS have been extremely positive. The true key to maximizing the return on an investment in the protocols is early communication among spacecraft, instrument and ground system developers to achieve a common understanding of data format definitions. Such communication reaps the benefits of an optimized design, which in turn maximizes cost avoidance, benefiting all system users.

REFERENCES

[1] *Packet Telemetry*. Recommendation for Space Data System Standards, CCSDS 102.0-B-3. Blue Book. Issue 3. Washington, D.C.: CCSDS, November 1992.

[2] *Advanced Orbiting Systems, Networks and Data Links: Architectural Specification*. Recommendation for Space Data Systems Standards, CCSDS 701.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, November 1992.

[3] *Time Code Formats*. Recommendation for Space Data Systems Standards, CCSDS 301.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, April 1990.

[4] *Interface Control Document Data Format Control Book for EOS-AM Spacecraft*. ICD-106. Greenbelt, MD: NASA Goddard Space Flight Center, April 1994.

[5] *General Interface Requirements Document for EOS Common Spacecraft/Instruments*. GSFC 422-11-12-01. Revision A. Greenbelt, MD: NASA Goddard Space Flight Center, January 1994.

[6] *Interface Control Document Between the EOS Data and Operations System and the Advanced Spaceborne Thermal Emission and Reflection Radiometer Ground Data System*. CDRL B311. Revision 1. Greenbelt, MD: NASA Goddard Space Flight Center, January 1997.

A PROPOSAL FOR IMPLEMENTING CCSDS STANDARDS FOR THE NOAA-N & N' MISSIONS

Diem V. Nguyen
Lockheed Martin
Seabrook, MD 20706

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ABSTRACT

The Polar Operational Environmental Satellite (POES) Program provides operational weather satellites. Developed by the National Aeronautics and Space Administration (NASA), funded and operated by the National Oceanic and Atmospheric Administration (NOAA), the POES satellites currently generate Time Division Multiplex (TDM) telemetry.

NASA Goddard Space Flight Center (GSFC) is performing a study to make changes to the POES-N and POES-N' satellites. Among the proposed changes is the adoption of Consultative Committee for Space Data Systems (CCSDS) Recommendations for telemetry and telecomanding. The implementation of CCSDS Recommendations for existing and new POES instruments including methods for Lossy compression of image data is discussed.

KEY WORDS

CCSDS Recommendations, Proposed Command & Data Handling (C&DH), and Data Compression Techniques.

BACKGROUND

The POES Program is a cooperative effort between NASA, NOAA, the United Kingdom (U.K.), and France. For more than 20 years, a constellation of low-earth orbiting POES satellites has been providing continuous global coverage of environmental data. NOAA plans to rely on the European Meteorological Operational (MetOp) Program, through the auspices of the European Space Agency (ESA) and the EUMETSAT organization, to provide morning meteorological satellite services through a “morning or AM” satellite beginning in 2003. NOAA provides afternoon meteorological satellite services through an “afternoon or PM” satellite. Depending upon the satellite’s equatorial nodal crossing time, these satellites are designated as AM or PM. Operating as a pair, the satellites provide data used for long-range weather forecasting. Total meteorological coverage will be accomplished by transferring global data back and forth between the US and European ground stations. Science data from each instrument will be packetized, multiplexed, and downlinked directly to multiple ground stations around the world using standard CCSDS protocols.

Goddard Space Flight Center is responsible for constructing, integrating and launching POES satellites. Operational control of the spacecraft is turned over to NOAA after on-orbit checkout, normally 21 days after launch. The POES satellites carry seven scientific instruments and two for Search and Rescue.

CCSDS RECOMMENDATIONS ADOPTION

The international space community which includes NASA, ESA, and 31 other member/observer agencies is committed to using the CCSDS Recommendations for low-earth orbiting satellites. Implementation of international standards will ensure the U.S. commitment to a growing international cooperation in space and global change research. NOAA is examining whether to implement CCSDS Recommendations on upcoming meteorological satellites. If implemented, it is expected that the data handling and direct broadcast subsystems of the POES, and the associated ground stations, will change to be CCSDS compatible.

PROPOSED C&DH SERVICES

The new C&DH function for the POES-N and -N' missions will be designed to perform CCSDS Telemetry and Telecommand packetization and transfer frame processing.

CCSDS Return Link Services

A candidate architecture generates CCSDS source packets and transfer frames on board the POES spacecraft and is depicted in Figure 1.

The return link CCSDS services are as follows:

- Path Service: Assemble raw telemetry from existing POES instruments and transform it into CCSDS packets prior to passing on to the Virtual Channel Data Unit (VCDU) service. Existing POES instruments include: Advanced Microwave Sounding Unit (AMSU), Advanced Very High Resolution Radiometer (AVHRR), Data Collection System (DCS), High Resolution Infrared Sounder (HIRS), Solar Backscatter Ultraviolet Radiometer (SBUV), and Space Environment Monitor (SEM).

- Virtual Channel Data Unit Service: Multiplex packets received from the Microwave Humidity Sounder (MHS) and new POES instruments into VCDUs prior to downlink. Potential new instruments for POES-N and POES-N' include: GPS Occultation Suite (GPSOS), Ozone Mapping Profiler Suite (OMPS), Cross Track Infrared Sounder (CrIS), and Integrated Multispectral Atmospheric Sounder (IMAS).

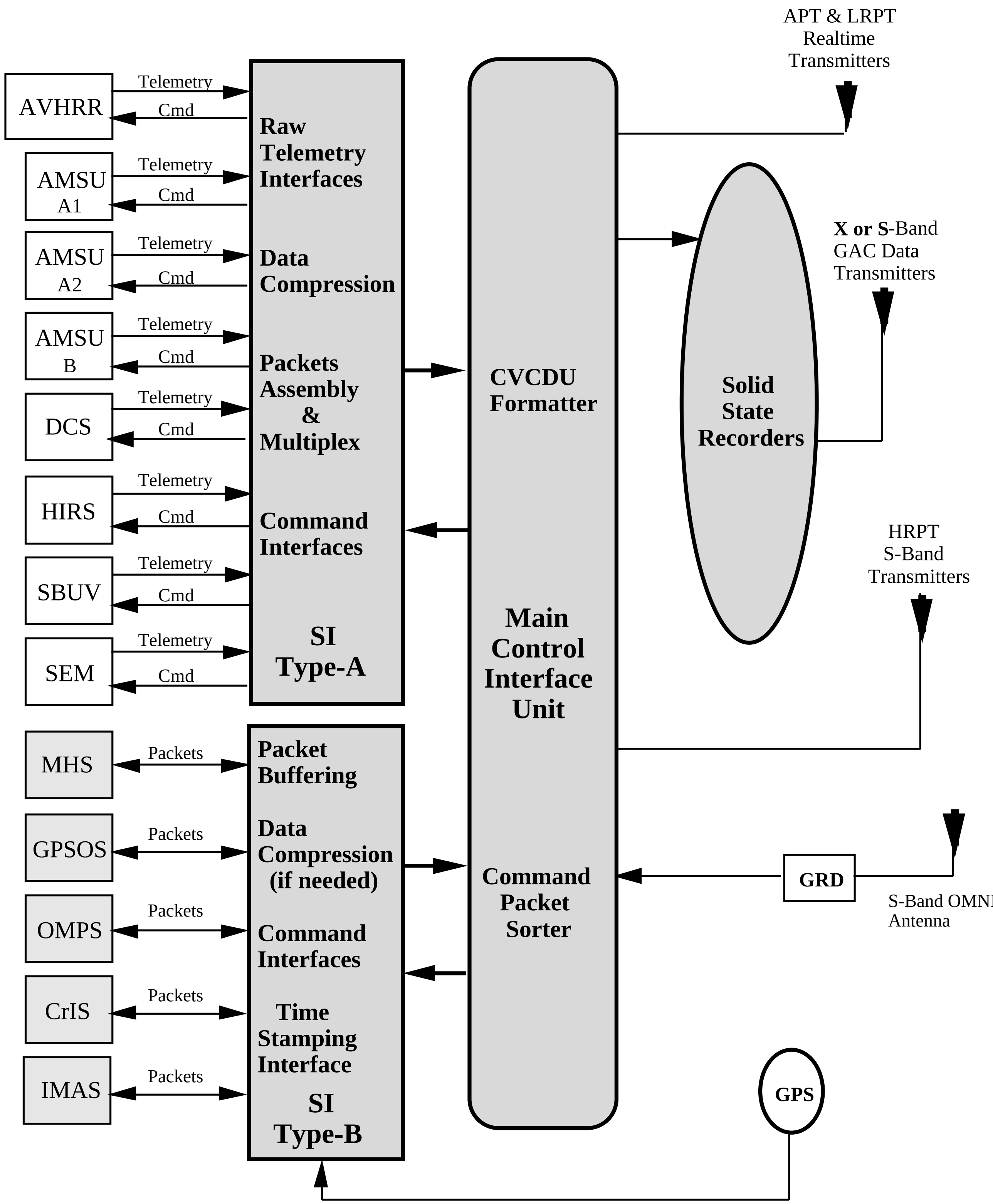

Figure 1. High-Level Block Diagram of New C&DH System

- Telecommand Data Routing Service: Extract status information from the Command Handling subsystem to form appropriate Command Link Control Words (CLCWs) for insertion into downlink Coded Virtual Channel Data Units (CVCDUs).

- Produce separate output streams of transfer frames for real-time broadcast High Rate Picture Transmission (HRPT), Low Rate Picture Transmission (LRPT), and transfer frames for playback of Global Area Coverage (GAC) data to ground stations.

- Data Compression Services: Compress GAC data using Lossless compression technique. Compress LRPT data using the Lossy compression technique.

CCSDS Forward Link Services

The forward link services are as follows:

- Create and terminate an association for a forward space link channel.

- Receive the CCSDS Command Link Transmission Units (CLTUs).

- Extract commands from a series of CLTUs.

- Pass commands to the Data Authentication Unit (DAU) for authentication.

- Generate a CLCW.

SERVICE INTERFACES

There will be two types of Service Interfaces (SIs). Service Interface Type-A will accept raw information from existing POES instruments. Service Interface Type-B will accept already assembled CCSDS packets from new POES instruments. Packets will be sent to a Transfer Frame Formatter for direct broadcast and recording.

Service Interface Type-A

Service Interface Type-A will accept the raw data from each instrument and assemble data into CCSDS Path Service Data Units (CP_SDUs) or CCSDS packets with a pre-assigned Application Process Identifier (APID). The Secondary Header Indicator parameter will always be generated to indicate the presence of a Secondary Header data structure (mainly for Time Code information) at the start of the CCSDS packet. Ancillary data can be optionally inserted in the Secondary Header data structure.

Service Interface Type-B

Service Interface Type-B will accept variable-length CP_SDUs from new POES instruments. This service interface will verify "Packet Sequence Count" field in the packet header. All valid, in-sequence packets will then be passed on to a Transfer Frame Formatter.

HIGH RATE PICTURE TRANSMISSION

The AVHRR data is de-interleaved so that pixels are sequential by band (see Figure 2). The data from each spectral band along with the space data and back scan data is then packetized and labeled with its unique APID. Packets containing data from each of the six AVHRR spectral bands and other instruments are broadcast in real time to end users over fixed-length CVCDUs. The spacecraft housekeeping data multiplexed with the science data will contain an attached CLCW required by the command operation protocol. In order to maintain a constant data rate out of the virtual channel multiplexer (i.e., an X number of VCDUs/second) a fill virtual channel may have to be inserted. This constant rate of VCDUs are then Reed-Solomon encoded to form CVCDUs, which are then randomized using a Pseudonoise (PN) pattern. The randomized CVCDUs are then transformed into a Channel Access Data Unit (CADU) by having a 32-bit synchronization pattern attached at the beginning. These CADUs are then passed to the convolutional encoder prior to the Radio Frequency (RF) modulation process.

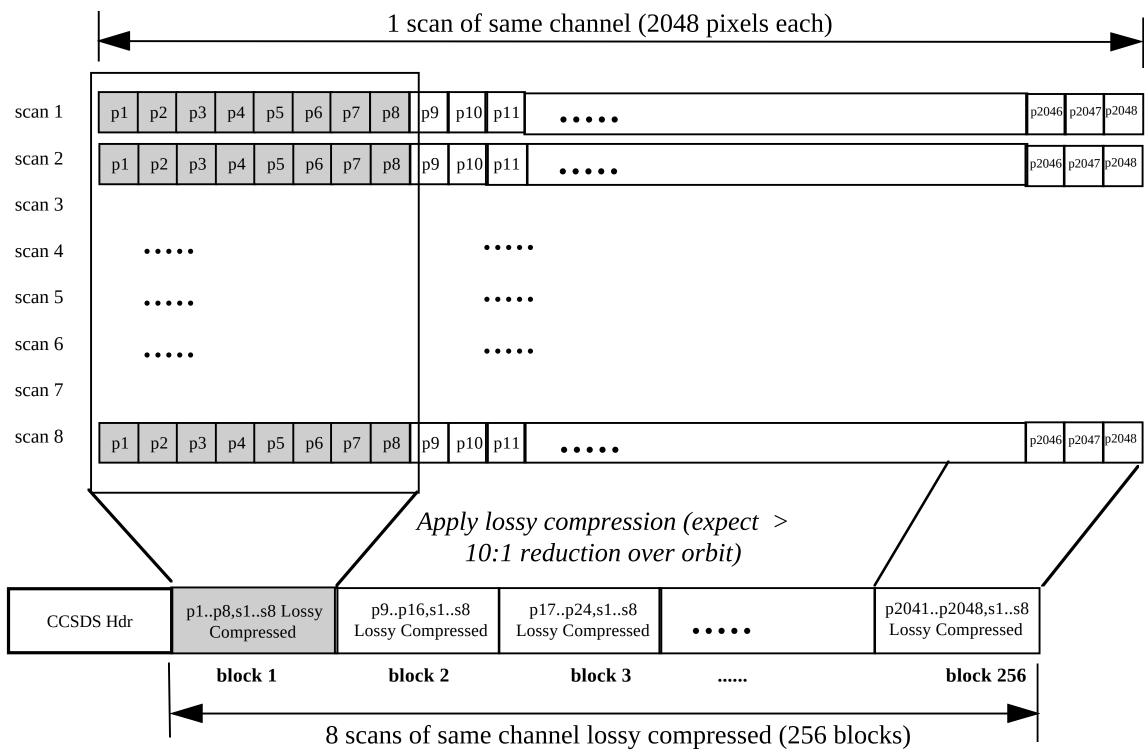

Figure 2. LRPT Compressed Stripe

COMPRESSION ALGORITHM

The current POES satellites transmit subsampled geometrically corrected images as analog video over VHF. However, the significant advantages in telemetry system simplification, the need for channel expansion, the inclusion of non-video sensor data, and the efficiencies gained operationally from the use of digital multiplexed systems have driven the need for low-rate picture transmission of digital imagery as a replacement for the current VHF Automatic Picture Transmission (APT) used with the NOAA-K, -L, and -M satellites.

Vertical and horizontal resolution, latency, background information, gray scale performance, performance in high Bit Error Rate (BER) environments, and edge definition are all critical requirements placed on instrumentation video systems. Video compression is one approach to reduce data bandwidth. Two video compression techniques for both playback AHVRR telemetry and LRPT data are proposed in the following paragraphs.

Lossless Data Compression

Lossless Data Compression is required by the science processing software performing the weather modeling. The Lossless Data Compression technique in compliance with the CCSDS 120.0-B-1 Blue Book [1] is recommended for playback data on POES-N and -N' satellites. The CCSDS Lossless Data Compression technique is based on the Rice algorithm, which is essentially a set of Huffman codes organized in a structure that does not require look-up tables. The set of Rice codes can be easily extended to cover the information range of the science data. They are adaptable to changes in the statistics of the data, and can be easily implemented. The structure of the algorithm also permits simple interface to data packetization schemes without having to carry side information across packet boundaries. Therefore, its performance is file-size independent.

Prior to recording the AVHRR data onto the Solid State Digital Recorders (SSDR), the demultiplexer separates spectral data into individual bandwith pixels ordered in the proper sequence. A unit delay predictor in the scan direction will be applied to the pixels for each spectral band. The output of the predictor will be sent to the entropy encoder in blocks of 16 samples. The compressed 16 samples will be formatted into one Coded Data Set (CDS). A CDS contains a four-bit option identifier followed by the compressed 16 samples. There will be 128 CDSs per scan line. After data compression has been performed, the resulting variable-length data structure is then packetized with an appropriate APID to identify each compressed spectral band and embedded in a VCDU prior to recording.

In the decompression processes the original source data is reconstructed from the compressed data by restoring the removed redundancy. The quantity of redundancy removed from the source data is variable and is dependent on the source data statistics. The reconstructed data will be an exact replica of the original source data.

Lossy Data Compression

Lossy data compression is acceptable for the low-rate direct broadcast service. The satellite also produces a high-rate direct broadcast in full resolution. The proposed Lossy Data Compression for the POES-N and -N' missions is based on a Modulated Lapped Transform (MLT), which has been shown to exceed the Joint Photographic Experts Group (JPEG) in both quantitative measurement and perceptual quality on still imagery. In the proposed technique, an MLT is combined with a Discrete Cosine Transform (DCT) to form the basic transformation. The MLT is applied along the scan-line direction and the DCT in the other direction. The hybrid transform enhances the performance of the more conventional DCT, and is termed the Enhanced DCT (EDCT).

In addition to the more compact transform, the proposed technique employs a Bit Plane Encoder (BPE) instead of the often used Huffman code. The BPE accepts the EDCT (eight-by-eight) spectral components and identifies component values present on each of the bit plane levels.

The processor accepts for transmission each component present from the most significant bit plane down to the bit plane which satisfies the required compression ratio.

The EDCT/BPE technique has the following advantages: 1) operates in real-time and requires no output smoothing buffer; 2) requires no upload processing tables; 3) requires no feedback control for rate control; and 4) accepts input pixel sizes from four to sixteen bits. A block diagram of the proposed EDCT/BPE encoder is shown in Figure 3.

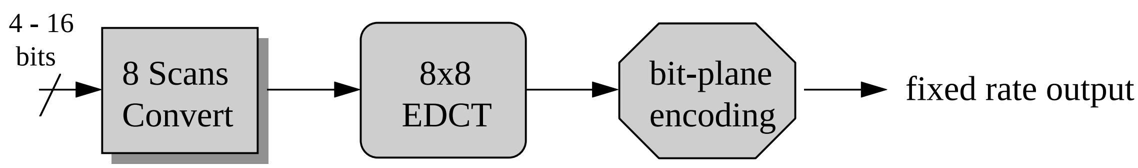

Figure 3. EDCT Encoder Block Diagram and Bit-Plane Encoding

In Figure 3, the format scan conversion unit takes eight scan-lines of input data and converts to overlapping sixteen-by-eight pixel blocks. The EDCT is used to transform the sixteen-by-eight pixel block into eight-by-eight frequency components, which are passed to the BPE along with the desired compression ratio. The compressed data from the BPE is then passed to a First In First Out (FIFO) buffer for packetization.

JPEG Compression

The JPEG compression is a transform coding method for still images based upon the DCT. The JPEG technique uses the DCT to convert spatial (pixel) information into the frequency domain. Visual energy is concentrated into a few frequency domain coefficients allowing higher compression than using the original spatial information.

The basic DCT has several functional parts shown in Figure 4. The system processes data in eight-by-eight pixel blocks. Each eight-by-eight block of data is transformed into a set of 64 DCT coefficients: one DC coefficient and 63 AC coefficients. The DCT coefficients are then quantized into one of 64 values from a quantization table. The DC term is the value of brightness (or chrominance) for the block. The other coefficients, the AC terms, are measurements of variation of picture content in the vertical and horizontal directions. The quantized coefficients are then prepared for entropy coding and the difference between the previous DC coefficient and current coefficient is encoded as well.

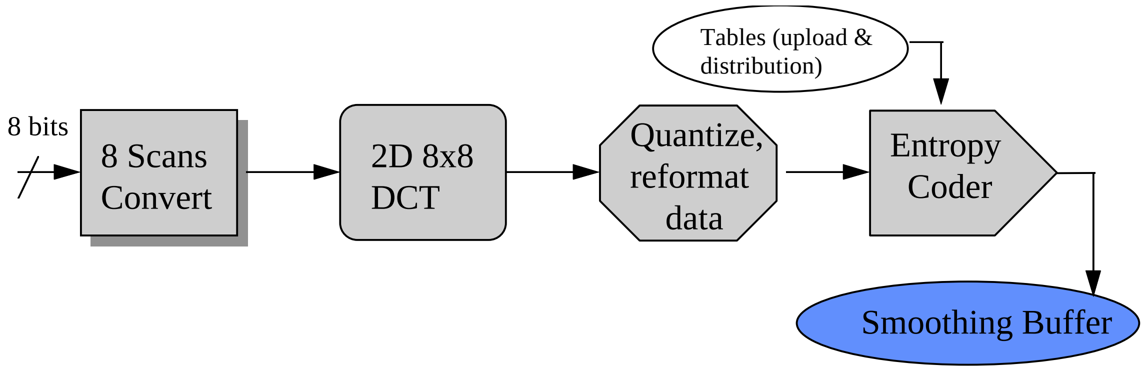

Figure 4. JPEG Compression System

The inherent "blocking or tiling" effect of the encoding process may cause objects to be moved slightly from their true positions and result in loss of edge definition and blurring. High compression ratios may cause halos, ghosts, and other artifacts of small objects and lettering to appear in the vertical and horizontal directions [2].

LRPT TRANSMISSION

The goal for the future digital LRPT/HRPT imagery service is to provide higher quality imagery than the current analog APT through increasing spatial resolution to one KM and increasing the number of channels to three, while being constrained to the current data bandwidth allocation of 72,000 bps. To achieve this goal, a Lossy compression technique that will reduce the HRPT raw data rate by a factor of ten is proposed.

Several system issues related to applying a data compression scheme on board a spacecraft must be addressed. These include the data packetizing scheme and how it relates to error propagation in case of communication data transport bit error occurrences, and the amount of smoothing buffer required when the compressed data is passed to a constant rate communication link. The proposed CCSDS layered architecture is an excellent proposal for transporting the compressed data. The CCSDS communication protocol provides for variable-length packets and a very powerful error correcting scheme that will provide an essentially "error free" channel.

In the LRPT system, three of the six spectral bands are selected for direct broadcast to LRPT users. These three spectral channels are passed to the EDCT/BPE to be compressed by a compression ratio of ten to one prior to being packetized. The total number of coding bits resulting from compressing a fixed number of data samples is usually a variable. The CCSDS data architecture provides a structure to packetize the variable-length data stream into packets identified with individual APIDs.

The EDCT/BPE will first capture a strip of eight scan lines for the given spectral channel into a ping-pong buffer. This buffer will output a block of 64 pixels arranged in eight-by-eight blocks (see Figure 2), until the strip is completed. The compressed strip of 256 eight-by-eight blocks will be inserted into the data field for one packet. The packet header will be attached along with the secondary header, which contains the time code.

The compressed spectral channel packets will then be transported over multiple CVCDUs along with the other science instrument data similarly to an HRPT data channel.

PLAYBACK TELEMETRY ON SOLID STATE RECORDERS

Solid State Digital Recorders will be used to store large amounts of digital data on board the POES-N & -N' spacecraft. The on-board SSDR will provide enough storage for global coverage for all scientific instrument data along with the AVHRR instrument data. Only AVHRR instrument data will be compressed using the previously described Lossless algorithm. Based on the AVHRR compression, the SSDR recorder capacity for the AVHRR data can be reduced by a factor of two.

When the SSDR is read out, the VCDUs for all instruments will be Reed-Solomon encoded and randomized before Attached Synchronization Markers (ASMs) are attached.

CONCLUSION

With the advent of CCSDS Recommendations and the availability of direct broadcast data from a number of current and future spacecraft, a large population of users could have direct access to Earth Science data. With the arrival of high performance, high integration, and low cost Application Specific Integrated Circuits (ASICs), a new class of telemetry processing equipment is possible at a fraction of the cost of traditional systems.

By employing efficient video compression techniques, CCSDS packetization, and virtual channel multiplexing schemes, NOAA can provide three quality video LRPT channels instead of two APT channels to end users at modest data rates outperforming the current TDM scheme.

Furthermore, EDCT/BPE compression accepts data in the range of four to sixteen bits parallel (instead of eight bits for JPEG); therefore, original ten-bit samples from AVHRR can be used to keep the same intensity (1024 versus 256 gray scales) level of the original image.

The application of CCSDS Recommendations allows a spacecraft development team and flight operation team to benefit from the valuable experiences gained during many NASA missions. Off-the-shelf hardware and software can be readily obtained, saving on development costs. CCSDS is a viable approach for the POES satellites.

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A CASE STUDY IN STANDARDS AND INTEROPERABILITY: THE TRANSFER OF MISSION OPERATIONS FOR STRV-1A AND STRV-1B

Randal L. Davis, Sean Ryan, Adrian Hooke[1]

ABSTRACT

During the summer of 1996, the day-to-day routine orbital operation of two active research satellites—the Space Technology Research Vehicles STRV-1A and STRV-1B—was transferred from the Defence Evaluation and Research Agency in Great Britain to the University of Colorado in the United States. This paper describes how the transfer of control of these two spacecraft was carried out and how use of the Consulative Committee for Space Data Systems standards made the transfer simpler and faster.

KEYWORDS

Satellite Mission Operations, Consultative Committee for Space Data Systems (CCSDS)

INTRODUCTION

Space Technology Research Vehicles STRV-1A and STRV-1B were built by the Space Department of the British Defence Evaluation and Research Agency (DERA) in Farnborough, England. The satellites were chiefly designed to demonstrate and evaluate new technologies for dealing with problems that beset satellites in near-earth space, including: erosion of spacecraft surfaces and components from reaction with atomic oxygen in the upper atmosphere; bombardment by ionizing radiation within the Van Allen Belts; and electrostatic charge buildup with subsequent—and potentially damaging—discharge. To provide maximum exposure to these hazards, STRV-1A and STRV-1B were launched into a permanent geosynchronous transfer orbit in June 1994. During each 10.5 hour orbit, the satellites sweep to within 200 km of the Earth's surface, slamming into the upper atmosphere at over 10 km per second, and then transit through the radiation belts, out into the solar wind to an apogee of 35,000 km, and then back again. In addition to the technology experiments, a set of scientific experiments characterize the radiation environment through which the satellites pass. (See Reference [1] for further details on the satellites, their mission, and the results of their investigations.)

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The original ground segment for STRV-1A and STRV-1B was developed and staffed by the DERA. This system underwent significant changes during the mission, most notably modifications needed to support testing of the proposed Spacecraft Protocol Standard that would extend Internet-like services to spacecraft. In September 1996, an even more radical change was made: day-to-day operations of STRV-1A and STRV-1B was transferred from England to the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) in Boulder, Colorado. It has been rare to transfer operations of orbiting spacecraft from one organization to another: the cost and effort of implementing a new mission operations system—or accomodating a different satellite with an existing operations system—has usually been prohibitive. The transfer of operations for STRV-1A and STRV-1B thus provided a unique opportunity to understand how to assess *interoperability:* the ability to support a satellite from two or more mission centers each of which is using different hardware, software and operational procedures.

THE ORIGINAL MISSION OPERATIONS SYSTEM

The original ground segment for STRV-1A and STRV-1B was located at the DERA's Lasham satellite ground station in Southern England. A 12-meter tracking antenna connected the ground segment to the satellites using S-band telemetry and command links that complied with NASA and European Space Agency standards. The highly elliptical orbit of the satellites allows for ground station contacts that can last for several hours. These long view periods compensate for the low telemetry data rate of 1000 bps. The downlink and uplink for the satellites are compliant with the packet telemetry and telecommand Recommendations of the Consultative Committee for Space Data Systems [2], [3], [4], [5]. There are always four packets within an STRV-1A or STRV-1B transfer frame: one packet per frame contains the status of uplink processing; the other three can contain real-time housekeeping data, or recorded data that is being played back, or (if no other data are available) idle patterns.

The real-time mission operations system for processing and displaying downlink telemetry data and for generating uplink commands was implemented on a set of personal computers under the MS-DOS operating system (see Figure 1). Bit-synchronized telemetry data were passed to the Data Handling Terminal, which synchronized on the CCSDS transfer frame, extracted packets from frames, and stored packets to disk. The extracted packets were passed to the Telemetry Workstation, which converted, checked, and displayed the data.

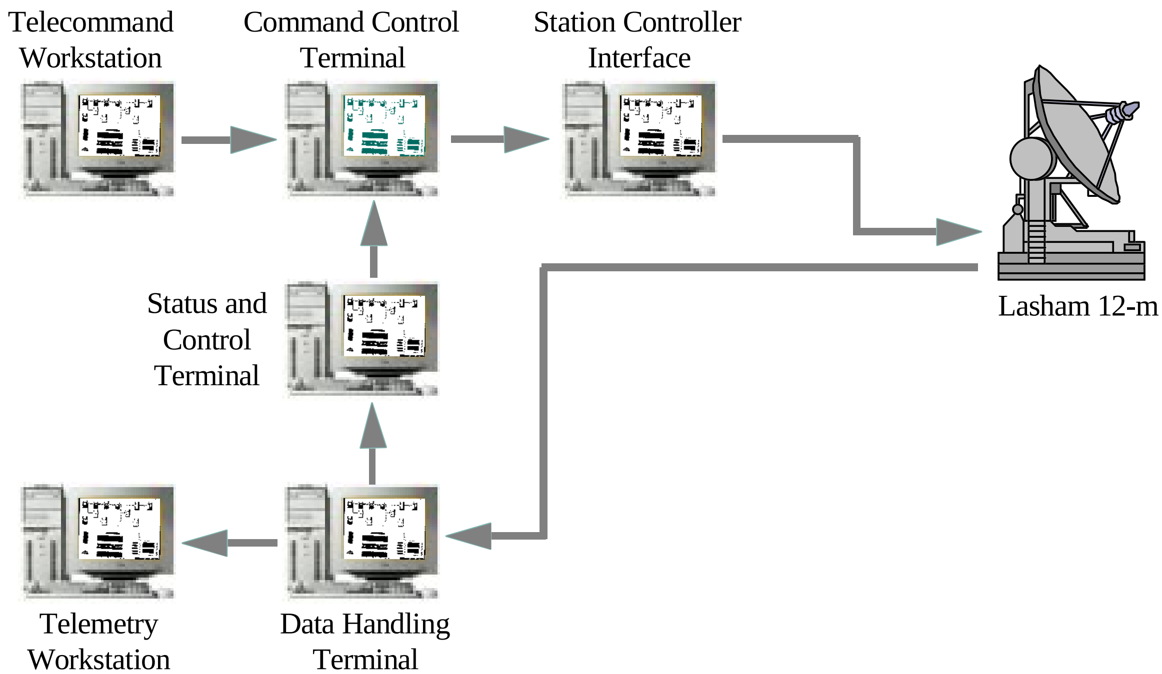

Figure 1. Original Implementation of the Ground Segment for STRV-1A and STRV-1B

On the uplink side, the Telecommand Workstation took commands in human-readable form directly from operators and could also execute prepared command scripts. Most operations for the satellites were carried out using such scripts. The Command and Control Terminal converted commands into telecommand packets and frames and then added error correction and detection coding to form Command Link Transmission Units. The Station Controller Interface then handled the modulation of CLTUs onto the uplink signal. The Status and Control Terminal implemented the CCSDS Command Operations Procedure (COP-1) whereby the ground system and spacecraft cooperated to assure that all commands were received without error and processed in the proper order.

Most non-real time mission operations functions, including orbit prediction and determination, attitude determination and control, command script generation, experiment data processing, and spacecraft performance analysis were carried out by DERA personnel in Farnborough. Command scripts were prepared by the Farnborough-based spacecraft operations managers on a daily basis and then forwarded via modem and an electronic bulletin board to the operators at Lasham. Data collected during a contact were placed on the same bulletin board for access by experimenters and engineers.

While the original mission operations system as described above worked well, a shortcoming with the satellites' communications systems made the uplink and downlink through the Lasham antenna marginal and problematic. To overcome the problem, the DERA requested support from NASA's Deep Space Network. Connections were added between the Lasham ground segment and the DSN, allowing the satellites to communicate through the 26-meter stations in California, Australia and Spain. The augmented ground system saw the STRV-1A and STRV-1B spacecraft successfully through their nominal one-year mission and a six-month extended mission.

In 1996 the ground system again evolved, this time to accommodate an experiment not foreseen when the spacecraft were built: the testing of advanced space-to-ground communications protocols. In 1993, a working group from NASA and the U.S. Department of Defense had identified the need for communications services beyond those provided by the typical satellite telemetry and telecommand links. This included file transfer capabilities, improved data protection and security, and the ability to better integrate space-ground links with terrestrial networks. The working group generated four protocol specifications for a Spacecraft Protocol Standard (SCPS), including an application layer file transfer protocol, a transport layer protocol, security layer protocol, and network layer protocol [6], [7], [8], [9], [10]. The DERA was interested in these protocols, and it was decided to use the STRV-1B satellite as an orbiting testbed for the transport, file and security protocols.

One of two identical computers on board STRV-1B was reprogrammed to implement the space side of the protocols. Capabilities were added to the ground segment at Lasham to allow for bent-pipe transfer of data between the STRV-1B spacecraft and a test center operated by the MITRE Corporation in Virginia. The ground segment for the SCPS-STRV Flight Experiment is shown in Figure 2. A personal computer running Unix was added to the ground segment to serve as a gateway between Internet and SCPS protocols. Test data coming from Virginia were converted into the STRV uplink format and transferred to the spacecraft through the existing command processing chain. On the downlink side, SCPS data from the spacecraft were stripped out by an interface box implementing the full CCSDS packet telemetry protocols, and the test data were sent to the SCPS Workstation and then onward via the Internet [11].

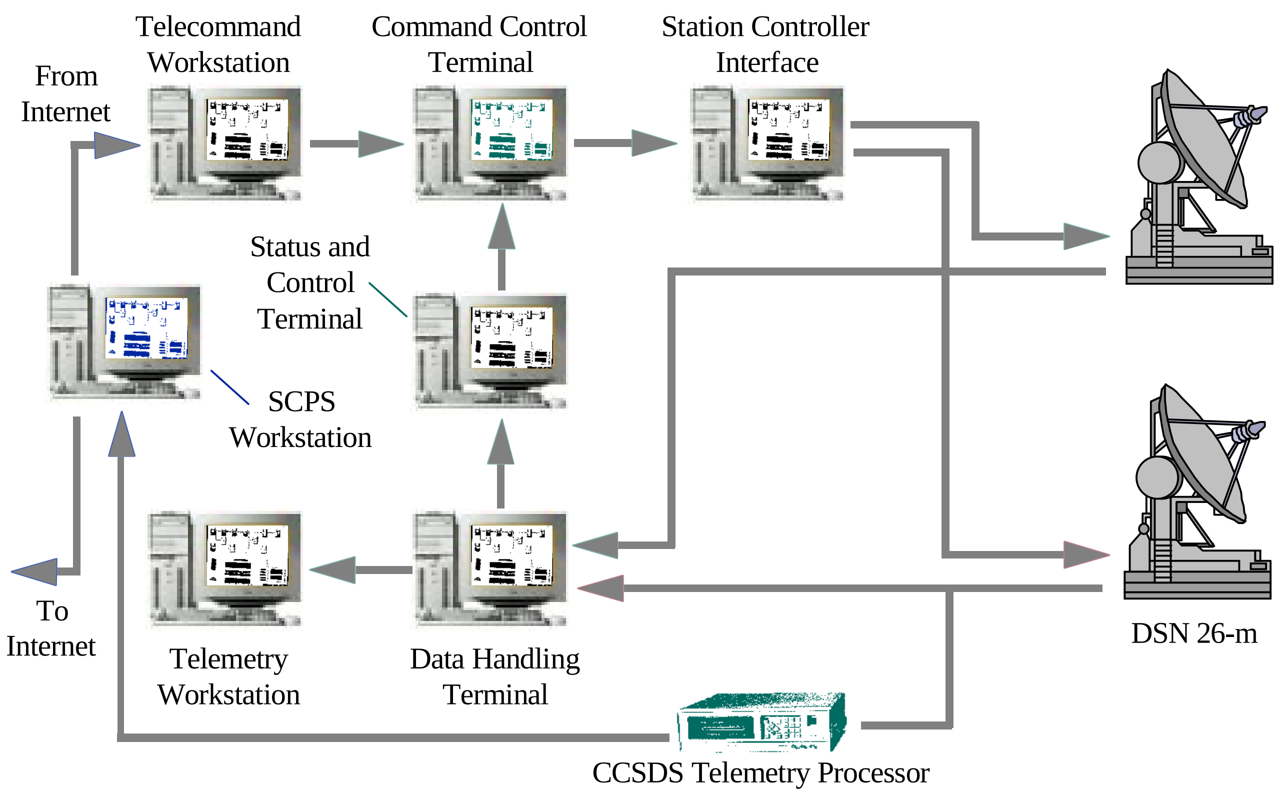

Figure 2. Ground Segment for the SCPS-STRV Flight Experiment

CREATING A NEW MISSION OPERATIONS SYSTEM

The DERA had decided to shut down STRV-1A and STRV-1B at the conclusion of the SCPS-STRV Flight Experiment in 1996, so that the Space Department could concentrate on two follow-on spacecraft (STRV-1C and STRV-1D). One of this paper's co-authors (Hooke), who had helped lead the SCPS effort, was impressed with the value of the STRVs as orbiting testbeds and began to float the idea of keeping the spacecraft alive for further experiments. His concept reached receptive ears at the University of Colorado's Laboratory for Atmospheric and Space Physics. LASP is one of the very few university-based research groups to ever operate spacecraft for NASA, having operated the Solar Mesosphere Explorer successfully from 1981 to 1989. LASP is also under contract from NASA and the Universities Space Research Association to build and operate a satellite called the Student Nitric Oxide Explorer. The SNOE (pronounced *Snow-ee*) spacecraft is similar to the STRV-1A and STRV-1B in many ways, and SNOE is fully compliant with CCSDS telemetry/command Recommendations. It was therefore felt that the mission operations system being developed for SNOE could serve the STRV spacecraft as well, although the schedule for implementing the system would have to be greatly accelerated.

LASP conducted a one-month study during April 1996 on the feasibility of transferring STRV operations. The initial findings were encouraging and funds were provided to travel to England in May and June to meet with the people who built and operated the spacecraft. A one week intensive introduction to the satellites and the ground system was provided by DERA personnel, followed later by a week of hands-on training in specific areas. By early June the LASP team had assembled a technical and cost plan for the effort. Approval from NASA and the DERA to proceed with the transfer was quickly forthcoming, but political considerations required negotiations at an even higher level. Spacefaring nations are bound by treaty to not take over the satellites of other nations. While these treaties clearly had hostile takeovers in mind, the issues they raised had to be addressed, and diplomatic discussions were conducted in parallel with the technical developments. The LASP mission operations system had to be fully operational within three months: if transfer of the spacecraft was not effected by the end of August, there would be no reprieve for them. Thus when the go-ahead was given, work proceeded quickly on four fronts: assembly of the hardware and software for the new mission center; development of needed operations procedures; access to the Deep Space Network; and selection and training of students to serve on the operations team.

From the outset it was recognized that LASP could not simply replicate the DERA ground system. The only hope of meeting the schedule was to adapt STRV operations to employ the hardware and software with which LASP was already familiar and proficient. This meant shifting from a PC-based system to one based on Unix workstations. A Sun Ultrasparc 1 computer was acquired to host most mission operations functions and an interface between the Sun workstation and the DSN was ready by mid-July (see Figure 3). The software for monitoring and controlling the satellites during real-time contacts, built from the Operations and Science Instrument Support Command and Control (OASIS-CC) package developed by LASP, was also in place by mid-July. The OASIS-CC software was augmented by the OASIS Interface System (OASIS-IS) for handling CCSDS telemetry and commanding. Originally developed for the SNOE mission, the OASIS-IS software was easily adapted for STRV, the chief difference being that STRV telemetry frames came from the DSN wrapped in NASCOM 4800-bit blocks, and so support for the NASCOM protocol was added to OASIS-IS. The OASIS-CC software could perform all of the functions of the Lasham ground system, except for the COP-1 command protocol. DERA software was installed on a PC to perform all post-pass data processing. This ensured that all of the data products going to experimenters would remain unchanged during and after the transfer of control. An important change was made, however, to the way in which the data were delivered to experimenters: rather than a bulletin board accessible via modem, LASP made all data available on the Internet.

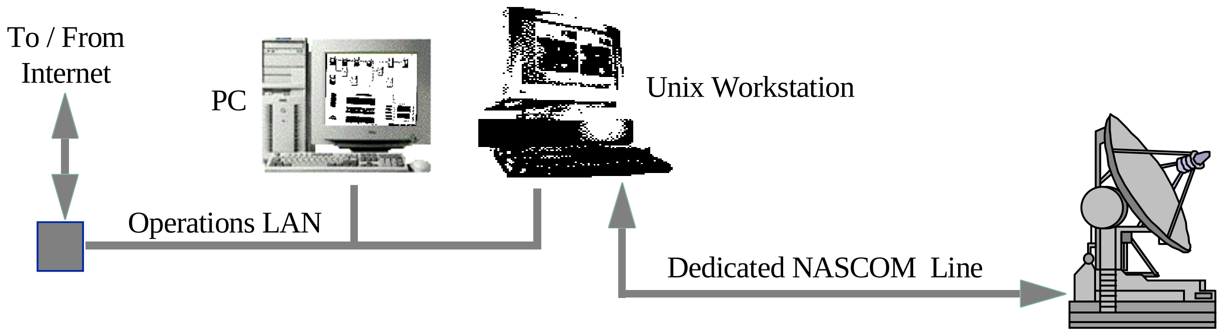

Figure 3. Hardware-Oriented View of the LASP STRV Mission Operations System

The OASIS-CC software package includes a specialized computer language for satellite operations called CSTOL. All of the command scripts that the DERA had developed to perform tasks like attitude control maneuvers, and science experiments had to be converted into CSTOL procedures. To simplify this transition and to make it easier to validate the new procedures, a one-to-one correspondence was kept between DERA scripts and CSTOL command procedures. LASP's OASIS Planning and Scheduling (OASIS-PS) software package was brought in to automate scheduling of spacecraft activities. After a schedule is generated, the OASIS-PS software can produce a master CSTOL procedure that sequences all of the command activities that are to be performed during a pass.

While the LASP mission operations system was being developed, parallel work was underway within the Deep Space Network. A set of dedicated voice and data lines was ordered and installed and tests run to verify readiness. DSN personnel worked closely with the LASP team to cut the time required to get the new control center online. By late in July, the LASP team was able to listen in during STRV passes with the DSN conducted from Lasham. By early August, LASP had data connections as well.

LASP's interest in satellite mission operations stems from the extraordinary opportunity it presents for students to learn how spacecraft actually work. Over 100 students were employed as spacecraft operators during the 8-year Solar Mesosphere Explorer mission, and these students exhibited a high degree of enthusiasm, commitment, and professionalism throughout. To prepare for the SME mission, new students went through three months of classroom training and tutelage at the control consoles from veteran student controllers. But there was no time for a prolonged training program for STRV. The first group of students was selected in June and intensively trained during a period of only three weeks. But the students quickly picked up what they needed to know and were ready when the transition from Lasham to LASP began.

BRINGING THE NEW SYSTEM ONLINE

By the end of the first week in August, all was in readiness to bring the new mission operations system online (see Figure 4). Two DERA spacecraft managers, John Eves and Angela Cant, flew to Colorado to be present during the transition. For the first week after their arrival, both Lasham and LASP received telemetry data from the satellites, but only the UK team issued commands. This allowed LASP to verify that downlink processing was working correctly. During the second week of the transition, LASP sent commands while Lasham watched. Not surprisingly, some problems were discovered in the command link, and on more than one occasion Lasham had to step in and put things right again. By the third and final week of the transition all of the downlink and uplink functions of the new mission operations system were validated, as were all of the operational procedures. Starting from the third week of August, non-real time functions like orbit prediction, attitude maneuver planning, and experiment data processing were performed at LASP, with frequent consultations back to DERA experts in Farnborough. On August 31, the Lasham ground station signed off and LASP became the sole operator of the spacecraft.

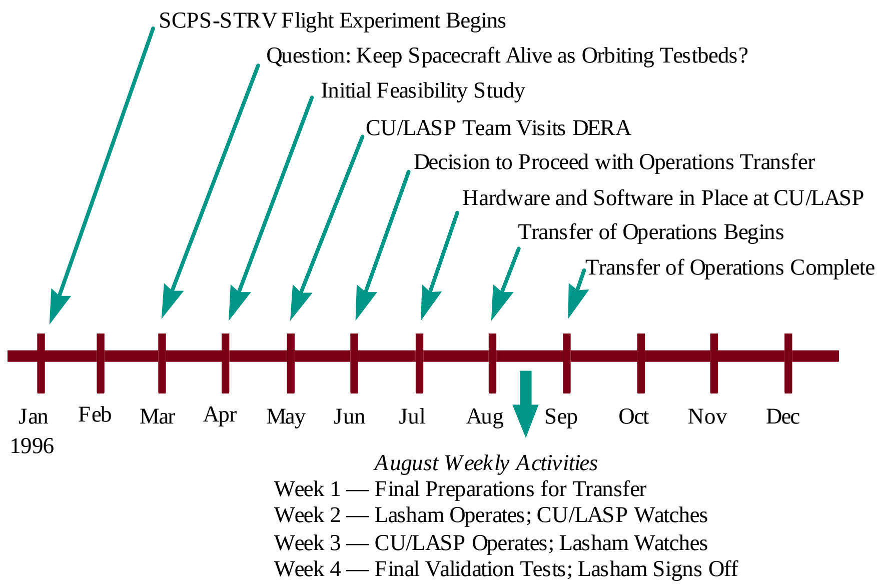

Figure 4. Timeline of Transfer of Mission Operations

The transition was completed in slightly over three months and at a cost well below $200,000. About $20,000 of new hardware was needed and $15,000 of new software. The remainder went for salaries and travel. Per current NASA practice, the cost of DSN support for the STRVs is not charged directly to the project. A total of about one person-year of effort was required to make the transition.

CURRENT STATUS

The new mission operations system for STRV-1A and STRV-1B has been working very well since the transfer of control in August 1996. Both spacecraft are active and generally healthy. Scientific investigations are being carried out using five of the vehicles' fourteen experiments and efforts are underway to use the spacecraft as testbeds for new mission operations techniques and technologies. In the course of these testbed experiments, the satellites will be operated using several commercial satellite control software packages. There are also plans to use the satellites for testing new space-to-ground communications capabilities. Sixteen students have gained hands-on experience as members of our mission operations team, and operating these satellites has helped immensely in preparing them for the upcoming SNOE mission. Another fifteen students have had the STRV mission as a case study in their classwork. The high degree of student involvement can be gauged by the fact that a graduate student in Aerospace Engineering (Ryan) is Deputy Mission Operations Manager.

CONCLUSION

Experience in transferring operations of STRV-1A and STRV-1B from DERA to LASP has demonstrated that it is possible to jointly operate spacecraft and to transfer control from one organization to another, even when the mission operations systems that are employed differ significantly from each other. We often dwell on the differences between satellite missions and emphasize the unique aspects of their ground systems, but the fact remains that most satellites are similar in their need for a few basic mission operations services—telemetry processing, command processing, scheduling, and so on. In the case of STRV-1A and STRV-1B, it was straightforward to map from the DERA implementation of these services to a new implementation in the LASP system. Some additional lessons learned:

Mission operations systems can be rapidly assembled from off-the-shelf components.

During the past several years, there has been a proliferation of software and hardware products designed for (or adapted to) spacecraft operations. Given the extremely short time that was available for creating the new operations system for STRV-1A and STRV-1B, there was no alternative but to use existing products throughout. Our experience in doing this for STRV was extremely positive. It was easy to identify a set of components that offered the needed services. For many operations functions there were a number of good off-the-shelf solutions from which to choose. For example, while LASP used their own OASIS-CC software for real-time operations, similar commercially available packages could probably have been installed and set up to perform STRV operations within the time available.

Spacecraft design and the availability of standards strongly affect the ability to interoperate satellites.

Several aspects of the design of STRV-1A and STRV-1B made them particularly well-suited for this project. For example, the dual computers onboard meant that we could keep the spacecraft flying safely on one computer while the second was used (and sometimes crashed) in testing. On the standards side, CCSDS packet telemetry and telecommand standards certainly eased the transition of operations. It took one person less than two weeks to modify LASP's existing telemetry and command processing software for use with STRV-1A and STRV-1B. We believe that the space operations community should continue to search for areas where commonality and standardization across missions can be established.

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LESSONS LEARNED FROM USING SPACE DATA SYSTEMS STANDARDS IN FLIGHT MISSIONS

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ABSTRACT

Recommendations by the Consultative Committee for Space Data System (CCSDS) have been used in the development and operation of spacecraft at the Goddard Space Flight Center (GSFC) since 1991. Applying the Recommendations has reduced the cost and risk of spacecraft development and flight operations and provided proven solutions to user missions. Spacecraft projects will benefit even further from a future standard for file transfer and from application layer standards for common spacecraft operations functions.

KEYWORDS

CCSDS, standards, spacecraft operations, protocols

INTRODUCTION

Space data systems standards have an impact on the development and test of a spacecraft prior to launch and the on-orbit operations. The systems used for spacecraft testing and for mission operations generate commands and monitor telemetry data to determine the configuration and status of the spacecraft components. Formerly, spacecraft would use similar, but not identical protocols and formats for telemetry and command data. In the 1980s, the CCSDS developed a suite of Recommendations for space data communications and related aspects of the space/ground link. The first GSFC spacecraft to use CCSDS was the Solar Anomalous and Magnetosphere Particle Explorer (SAMPEX), launched in 1991. CCSDS Recommendations have been used for almost all Goddard Space Flight Center flight missions since then.

CCSDS

The CCSDS is a multi–space agency group, with members from North America, Europe, Japan, and elsewhere around the world. This committee was established in the early 1980s to assist in standardizing the space/ground links of the various agencies to increase the interoperability of their spacecraft and communications systems. The procedures of the CCSDS are described in reference [1]. CCSDS has established Recommendations for telemetry, telemetry coding, commanding, time codes, data formatting, and radio frequency and modulation. The telemetry and telecommand Recommendations are the ones that most directly impact the development and operation of flight systems.

The telecommand Recommendations define the formats, coding, and protocol for commanding a spacecraft. The protocol and coding assures a high probability that only correct, in-sequence commands are accepted by the spacecraft. The protocol provides an efficient mechanism for uplink to on-orbit spacecraft, where the communications latency is within a few seconds. The command protocol depends on a Command Link Control Word in the telemetry data to handle the acknowledgments. The command protocol also has features that allow the protocol to be bypassed. These features are typically used in non-nominal situations. The telecommand Recommendations are described in references [2], [3], [4], and [5].

There are two telemetry Recommendations. The first, Packet Telemetry [6], was developed in the mid-1980s and features up to 8 virtual channels. The second, Advanced Orbiting Systems (AOS) [7], was developed in 1989 for potential application to missions such as Space Station. AOS telemetry accommodates a more diverse set of data types, including voice and video. A subset of the AOS Recommendation, the Path Service, is similar to Packet Telemetry except that it supports 64 virtual channels.

CCSDS telemetry has two primary data constructs: the telemetry packet and the transfer frame, for Packet Telemetry, or Virtual Channel Data Units (VCDU), for AOS. The telemetry packet is a logically connected set of parameters. Telemetry packets are carried by a stream of fixed-length transfer frames/VCDUs, which provide a means of frame synchronization and error correction encoding. Each transfer frame/VCDU has a virtual channel identifier associated with it. These identifiers allow the downlink to be treated as if it is composed of multiple virtual downlinks. Virtual channels are used to differentiate data types, for example, real-time data from recorded data and science data from engineering data.

HISTORY OF CCSDS USE FOR FLIGHT MISSIONS AT GSFC

The original CCSDS telemetry Recommendations were defined in 1984, and the telecommand Recommendations were defined in 1987. The first mission to use both CCSDS telemetry and telecommand was SAMPEX, the first spacecraft from the Small Explorer Project. Other GSFC spacecraft that were developed in the 1980s (Hubble Space Telescope, Gamma Ray Observatory) used some of the CCSDS concepts but were designed prior to the completion of the CCSDS Recommendations. SAMPEX was built in-house by GSFC and was launched in July 1991. Four subsequent Small Explorer spacecraft were also built using these Recommendations. Another spacecraft built in-house at GSFC, the X-Ray Timing Explorer (XTE), was launched in 1995. This spacecraft uses the same telecommand Recommendations as the Small Explorers, and uses the AOS telemetry Recommendation instead of Packet Telemetry. This approach is being used by several other GSFC missions under development, including the Tropical Rainfall Measuring Mission, the first Earth Observing System (EOS) mission, and the Microwave Anisotropy Probe (MAP). This approach is expected to be used for all spacecraft developed by GSFC or developed elsewhere but managed by GSFC. Table 1 shows the usage of CCSDS telecommand and telemetry Recommendations by GSFC missions launched or to be launched from 1991 through 2000.

Table 1. CCSDS Usage by GSFC Missions

GSFC Mission	Spacecraft Builder	Launch Date	Telecommand	Telemetry
SAMPEX	GSFC	1991	Compliant	Packet Telemetry
FAST	GSFC	1995	Compliant	Packet Telemetry
SOHO	ESA	1995	No	AOS
XTE	GSFC	1995	Compliant	AOS
Wind/Polar	Lockheed-Martin	1995, 1996	No	No, time division multiplexed
ACE	APL	1997	Similar; modified error control, status reporting	Time division multiplexed within CCSDS frames
TRACE	GSFC	1997	Compliant	Packet Telemetry
TRMM	GSFC	1997	Compliant	AOS
EOS-AM	Lockheed-Martin	1998	Compliant	AOS
Landsat 7	Lockheed-Martin	1998	Similar, but not fully compliant	Time division multiplexed within CCSDS frames
WIRE	GSFC	1998	Compliant	Packet Telemetry
New Millennium E0-1	Litton	1999	Compliant	AOS
SWAS	GSFC	1999	Compliant	Packet Telemetry
IMAGE	Lockheed-Martin	2000	Compliant	AOS
MAP	GSFC	2000	Compliant	AOS

The XTE spacecraft implementation represents a good example of CCSDS use at GSFC. Each spacecraft subsystem is assigned a range of packet Application Process Identifiers (APIDs). This enables the APIDs to uniquely identify the source of the data. The data in the telemetry packets is collected by distributed data collection nodes in the subsystems. The telemetry packets are sent via a local area network to a central data collection subsystem, the Command and Data Handling subsystem (C&DH). The C&DH assembles the real-time telemetry data stream and records the telemetry data for later high-speed playback.

The XTE C&DH flight software multiplexes the telemetry packets into streams of VCDUs. Packets are selected, filtered, and organized into a number of virtual channels. The virtual channels are used to filter and/or route the data according to broad categories, such as real-time housekeeping, real-time science, playback housekeeping, and playback science.

The XTE C&DH also filters the data based on APID. The filter tables allow the C&DH to transmit and/or store every Nth packet received from the spacecraft subsystems. XTE filters packets for downlinking at frequencies between 1 and 1/256 of their on-board rates. Through the use of this filtering of packets, the housekeeping data collection rate on-board is 64 kilobits per second (kbps), the real-time housekeeping downlink rate is 16 kbps, and the housekeeping data storage rate is 9 kbps. This filtering scheme, enabled by the use of CCSDS Recommendations, allows the downlink data content to be adjusted by adjusting the filters, without modifying the on-board software.

The XTE C&DH also receives and distributes commands to each subsystem via the same network interface. Only one command virtual channel is used for XTE routine commanding. The C&DH processes each command and routes it to its destination based on the command APID. A second virtual channel is used for hardware discrete commands in order to allow a simple hardware decoder to be implemented on the uplink card. The virtual channel change allows the decoder circuitry to differentiate the special hardware commands from the normal commands based on the first 16 bits of the CCSDS command header.

BENEFITS OF CCSDS

Through the use of the CCSDS Recommendations, the mission implementation and operations have benefited by:

Enabling reuse

The system used for integration and test and for operations can be reused on other missions that use the same data system standards. This option provides the potential for large cost savings through the reuse of systems for missions that adhere to the same known and published standards. In addition, the operations risks are reduced because flight operations team members can re-apply the experience gained during operations on one mission to another mission that uses the same standards.

Lowering the risk of transmitting command and receiving telemetry data

By using a standard method for command and telemetry data rather than the ad-hoc methods previously developed for each mission, a project is assured that the protocols are mature and complete. Using the CCSDS Recommendations lowers the risk of the protocol's being incomplete or having unintended consequences, because it has been evaluated in detail by experts from many space agencies and has been used by other spacecraft. The CCSDS telecommand Recommendation is a sophisticated protocol that offers better uplink utilization and more efficient recovery from communications errors than previous methods.

Using the CCSDS path service for formatting telemetry data

In previously used Time Division Multiplex (TDM) systems, the C&DH synchronously collected telemetry from different sources. The format of the data was a set of minor frames organized into a major frame. Telemetry points from the entire spacecraft were assigned specific positions within the major frame. Each mnemonic format and location was assigned globally by the data system engineer for TDM formatted telemetry. Modifications to the telemetry format were managed centrally and this was a very resource-intensive job, especially for projects in which subsystems and instruments were developed in geographically remote locations. In contrast, by using the CCSDS path service, each subsystem is simply allocated a telemetry rate budget. The telemetry is multiplexed at the packet level and the details of the packet contents are left to the respective subsystem engineer. Only the total bandwidth is managed centrally, to ensure that the sum of the data generated by the subsystems does not exceed the downlink data rate.

Simplifying the monitoring and the managing of the bandwidth
With TDM, only a handful of telemetry modes were available for diagnostic use, such as memory dump mode, science mode, and engineering checkout mode. The diagnostic capability was severely limited in flexibility and had to be predefined at a detailed level. CCSDS formatted telemetry enables the mission to be much more flexible. For example, in the XTE implementation, on-board telemetry is communicated among subsystems with only a subset of the packets provided to the telemetry downlink. Subsystem telemetry is filtered for the telemetry downlink, with every Nth packet (different for each APID) routed to the transmitter. Each subsystem can manage its overall telemetry format and bandwidth simply by assigning appropriate filter factors to each of its different packets. XTE assigns different filter factors for its solid state recorder versus the real-time downlink.

The modification of a TDM format required replacing some data (often science data) with diagnostic data. Flight software or data commutation tables were rewritten. The operational flexibility of the CCSDS implementation was demonstrated when diagnosing the performance of XTE's star trackers. Star tracker packets are routed to the on-board attitude determination process at a frequency of 10 Hz. However, the packets are normally downlinked at a rate of only 1 Hz. When XTE attitude control system engineers detected anomalous behavior in the star tracker, the filter factor was updated to route the star tracker packets to the solid state recorder at the full rate of 10 Hz. The attitude control system engineers were able to receive the full data stream to diagnose the problem without affecting other subsystems and without changing the real-time bandwidth. The only modification to the telemetry format required was a single table element update and was accomplished within one day after management approval.

Using Commercial-Of-The-Shelf (COTS) hardware for telemetry decoding
The decoding of the data is performed in the operations control center for some missions. Use of the CCSDS Recommendation for coding has allowed these systems to use COTS decoders rather than more expensive and less proven custom decoders.

LESSONS LEARNED FROM THE USE OF CCSDS RECOMMENDATIONS

The CCSDS Recommendations are detailed, but they are vulnerable to individual interpretation. Two different organizations can take the same Recommendation and develop systems that will not interoperate completely. Implementers of systems based on CCSDS Recommendations should discuss their concepts with CCSDS experts to verify that they are interpreting the CCSDS documents correctly and to benefit from the lessons learned by other implementers. In addition, new CCSDS implementations need to carefully examine the influence that legacy elements may impose on the design and selection of CCSDS options.

End-to-End System Engineering

A significant lesson to be learned has to do with the process by which most missions went about designing the end-to-end, spacecraft-to-end-user data system. In some cases, the space segment of the data system was designed well ahead of the ground segment. The data system would be optimized for most effective utilization of on-board resources, but the impact to the ground segment was not considered until later. By the time these impacts were recognized, it was often too late to make adjustments on-board. This resulted in either costly additional software, additional operations workload, or both. The SOHO accommodation of the Michaelson Doppler Interferometer (MDI) instrument is a good example. The MDI instrument was based on a heritage design and its interfaces were used without modification. The MDI could not accept a spacecraft timing source to time stamp the packets that it generated. All of the other data sources on-board did provide a time stamp in the packets. This caused a problem for the ground processing of the data. Not only did MDI not provide a time stamp in the packet header (which is important to perform Level-0 processing), but it also differed from the rest of the spacecraft subsystems. This resulted in the development of a custom subsystem within the Level-0 processing software just to handle MDI data. This type of problem can be solved by effective systems engineering of the end-to-end data system. The mission must be designed end-to-end in order to make most effective use of CCSDS or any standard. Even more effective would be systems engineering of data systems across missions.

Selection of Class and Grade of Service

The CCSDS Recommendations are designed to encompass the requirements of a diverse set of users and organizations. The Recommendations include a variety of features and options to choose from. For example, the AOS Recommendation identifies six different services, each with up to three grades of service. The use of this Recommendation on GSFC missions has so far been limited to only one of the services (the path service) and one grade of service (grade 2: in-sequence and error free, but possibly incomplete). Users of CCSDS Recommendations need to select the subset of features and options that best meet their requirements. If interoperability with other organizations is required, the selected subset needs to include the features required to work with the other organization’s system.

Loss of Timing Relationships

The use of packets for the spacecraft status telemetry provides a flexible mechanism for reporting the configuration and state of the spacecraft. However, some of the timing relationships inherent in a time division multiplexed telemetry scheme could be lost in a packet telemetry implementation. Users need to think through their requirements for the timing of parameters and events and the relative timing between samples of a parameter when designing the packet telemetry implementation.

CCSDS Overhead

The overhead associated with CCSDS can be larger than that associated with TDM telemetry. The VCDU header and Reed-Solomon encoding symbols add approximately 16% overhead to the telemetry. Packet header overhead depends on the size of the data packets. For example, the average packet overhead for XTE engineering data is about 12% with a range from a low of 1.5% and to a high of 43% for the smallest packets.

Performance Requirements

The Submillimeter Wave Astronomy Satellite (SWAS) has a mode for initialization where the bandwidth is filled with very small status packets from the Attitude Control System. The data portion of these packets is smaller than the packet header and at high downlink rates result in nearly 15,000 packets per second. This exceeded the initial capabilities of the ground system. The more flexible data formatting capabilities enabled by the use of CCSDS require more analysis of the performance implications of the downlink design. In addition, this is an example of where early coordination among the spacecraft and ground system developers is needed to ensure compatibility.

Delegation of Packet Content Control

The use of packet telemetry allows the control of the contents of the packets to be delegated to the subsystem designers. This decentralization is enabled by the telemetry Recommendations, but is not part of the Recommendations themselves. If the control of the packet content is delegated, a bandwidth budget should be allocated along with it. Several GSFC missions had a significant oversubscription of the available bandwidth when all of the initial subsystem implementations were integrated, requiring a few iterations to make the data fit.

Data Bypass

A goal of the CCSDS telemetry Recommendation is to allow the operations center to receive only the subset of the data that it required to monitor the space components. All of the voluminous science data would not have to go to the operations center, as it did in TDM telemetry implementations. This significantly reduces the volume of data that the operations center handles. This goal has been elusive, however. Several missions have found late in their development that certain parameters in the science data stream were required in the operations center in order to perform data accounting or instrument performance evaluation. Future missions that wish to accomplish this goal will have to exercise more foresight in identifying the subset of data required in the operations center early in the design phase.

FUTURE NEEDS FOR CCSDS RECOMMENDATIONS

File Transfer Protocol

CCSDS has provided a set of Recommendations for the space/ground communications link. Further, the CCSDS is considering an extension of their Recommendations to support file transfer between ground and space. This protocol would be used to move data from on-board solid state recorders to the ground, to uplink software and tables, and to downlink memory dumps. This Recommendation will benefit flight operations, since these functions are all implemented in different ways by different spacecraft builders. The benefits of this Recommendation are similar to those of the existing Recommendations—a robust and proven protocol, reuse of flight operations software, and reuse of flight operations team experience from mission to mission.

Past experience and emerging future requirements suggest that a file transfer protocol must:

a. accommodate data rates up to 100s of million bits per second (for missions such as EOS);
b. accommodate moderate communications latencies of 5 seconds or less;

c. provide bi-directional file transfers both from the ground to the spacecraft and from the spacecraft to the ground;
d. be consistent with the existing CCSDS Recommendations;
e. span space/ground contacts;
f. internetwork with standard ground file transfer protocols.

Supercommutation

In the XTE C&DH implementation, each telemetry packet contains a single sample of each telemetry data point. The set of samples is collected, time tagged, and included into a single telemetry packet. For small sets of data collected frequently, the bandwidth associated with the header and time tag could be substantially larger than the data bandwidth. A convention has been established for future missions to collect multiple sets of the telemetry data sets and to concatenate them together into a single packet, thereby reducing the relative overhead of the header and time tag to arbitrarily low levels. A CCSDS Recommendation for this process, called supercommutation, would be beneficial.

Application Layer Standards

Spacecraft development and flight operations will benefit from applications layer standards that would standardize functions common to most spacecraft. Some examples are stored command formatting, on-board processor logs, flight software table formats and loading and dumping mechanisms, and on-board data management. These functions are implemented in similar fashion from spacecraft to spacecraft. Standards in these areas will allow even greater autonomy in the flight and ground data systems development and in operations. However, as application layer functions, they must be integrated with the more mission-unique spacecraft functions. It may be difficult to define a flexible and efficient interface between standard applications functions that would be widely adopted. The challenge with application layer standards is that standardization tends to constrain future innovation. CCSDS should explore the feasibility of application layer standards, but should not commit to them unless there is a consensus for the need for these standards among the member organizations of CCSDS.

CONCLUSION

The use of CCSDS Recommendations has provided GSFC flight missions with robust and capable protocols for command and telemetry data. It has reduced costs by increasing the reuse of existing solutions and has lowered risk by allowing spacecraft testing and flight operations teams to reuse their experience from one mission to the next. CCSDS use for telemetry enables improvements in the efficiency of the process of formatting the telemetry for a mission. However, the CCSDS Recommendations should be implemented in consultation with CCSDS experts, since they can be improperly applied in ways that were not intended by the Recommendations, and in ways that will not interoperate with other CCSDS implementations. CCSDS Recommendations should be extended to include file transfer protocols to provide a standard mechanism for moving large amounts of data between space and ground. In addition, CCSDS should investigate the feasibility of establishing applications layer standards between the spacecraft and flight operations function.

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These documents are available at "http://www.ccsds.org/ccsds/".